Progress in simulation of ITER First Plasma operation

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1. Introduction

The ITER Poloidal Field (PF) system comprises a segmented central solenoid (CS) and six outer PF coils [1], [2]. All PF coils and all CS modules, except for the two central modules, have independent power supplies. The two central CS modules are connected in series in a common circuit. To support plasma initiation, the PF system uses a set of resistors of the Switching Network Units in 5 CS circuits and in the circuits PF1 and PF6, as well as pre-programmed voltages of AC/DC converters in all 11 circuits of the CS and PF coils.

First Plasma operation is expected to be performed in ITER without blanket modules (with temporary stainless steel limiters), in a toroidal magnetic field of 2.65 T at 6.2 m (half of the nominal value), with a partly charged central solenoid (20kA in each module). The requirements on the First Plasma current are as follows: it should be higher than 0.1 MA during more than 0.1 s, but lower than 1 MA for less than 3 s. The latter is to protect (in the case of disruption) the vacuum vessel housings used to attach the temporary limiters to the vacuum vessel for First Plasma operation. After First Plasma operation, the temporary limiters will be removed and the housings will be used to attach the blanket modules. To obtain at least 0.1 MA for at least 0.1 s, complete impurity burn-through is not necessary and steel can be used for the temporary limiter material. Moreover 0D plasma transport studies have shown that the steel limiters provide passive protection of the vacuum vessel housings, since the plasma current is unlikely to increase to 1 MA due to the influx into the plasma of high Z impurities (Fe). However, for active protection of the housings, the rise of plasma current will be stopped at about 0.5 MA by feedforward or feedback zeroing the coil converter voltages (see the DINA simulation in chapter 3). This paper presents progress in simulation of ITER First Plasma operation since it was reported in [3].

2. First Plasma studies with 0D plasma transport model

0D plasma transport studies were performed with the SCENPLINT code assuming: hydrogen prefill gas, a single impurity Fe (the Fe influx to the plasma is described by physical sputtering of the limiter due to the wall bombardment by hydrogen and Fe ions), a vacuum vessel volume (the volume of prefill gas) of 1700 m^3, a recycling coefficient of hydrogen $Y = 1$, no gas puffing during the plasma initiation, the limiter inboard location at $R_{\rm lim} = 4.1$ m, major and minor radii of the breakdown region and initial plasma $R = 5.7$ m and $a = 1.6$ m, respectively, voltage produced by the PF system and currents in the vacuum vessel at and after the gas breakdown $U_{\rm ext} = 10.6$ V ($E = 0.3$ Vm^{-1}). The studies were performed taking into account the Dreicer mechanism of runaway electron (RE) generation and their avalanche multiplication.

The studies have shown that the range of prefill gas pressure, p, required for First Plasma initiation is very narrow: ≈0.3 mPa < p < ≈0.7 mPa, assuming a minor radius of the plasma of 1.6 m and a recycling coefficient of $Y = 1$. It was shown that the gas pressure lower limit, $p \approx 0.3$ mPa, is defined by the generation of RE. At the gas pressure 0.3 mPa, when the plasma current increases to ≈0.6 MA (during 1.3 s after the gas breakdown), the fraction of RE current becomes more than 50%. The gas pressure upper limit, ≈0.7 mPa, is set by insufficient ionization. At the gas pressure 0.7 mPa, the plasma current increases to ≈ 0.6 MA within 1.3 s, when the resistive loop voltage almost achieves the voltage produced by the PF system, stopping the further increase of plasma current. With the increase of the prefill gas pressure to values higher than this upper limit, e.g. to 0.75 mPa, the maximum value of plasma current reduces quickly to less than 0.05 MA, which is less than 0.1 MA required for First Plasma operation. Figs. 1a, 1b and 1c show waveforms of the plasma current and RE current obtained in the First Plasma simulations performed with the SCENPLINT code assuming the prefill gas pressure

0.3 mPa, 0.7 mPa and 0.75 mPa, respectively. The upper limit on the gas pressure at First Plasma operation reduces with reduction of the plasma minor radius assumed in the SCENPLINT simulations.

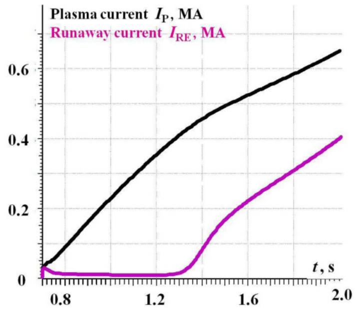

Fig. 1a: Plasma current (black) and RE current (red) at p = 0.3 mPa

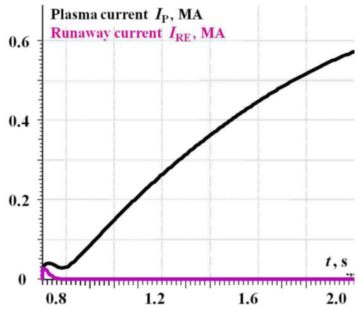

Fig. 1b: Plasma current (black) and RE current (red) at p = 0.7 mPa

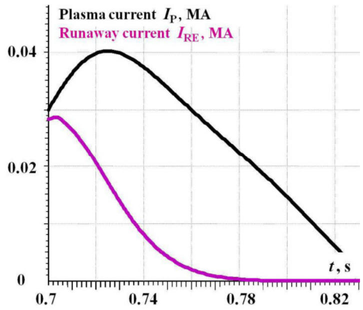

Fig. 1c: Plasma current (black) and RE current (red) at p = 0.75 mPa

The SCENPLINT simulations were performed with and without ECH, assuming 6.7 MW of ECH power injected into the plasma (2nd harmonic resonance at 2.65 T) and a single pass of the beam through the plasma region. These simulations demonstrate practically similar results, because the ECH power absorbed in the plasma is significantly less than the Ohmic heating power (see Fig. 3c). However, the ECH may increase reliability of the gas breakdown [4] by increasing the degree of pre-ionization, which is not simulated with the SCENPLINT code. Reduction of the recycling coefficient from $Y = 1$ to $Y = 0.85$ leads to a decrease of the electron density, increasing the RE current (to 0.4 MA at p = 0.7 mPa and $Y = 0.85$). A low recycling can be compensated by a strong gas puffing after the breakdown ($3.4 \cdot 10^{20}$ s^{-1} at p = 0.7 mPa and $Y = 0.85$). Increase of the recycling coefficient from $Y = 1$ to $Y = 1.5$, leads to an increase of the electron density and a reduction of the electron temperature, reducing the maximum value of the plasma current (to 0.5 MA at p = 0.7 mPa and $Y = 1.5$).

3. Design and simulation of First Plasma scenarios

First Plasma scenarios were designed using the TRANSMAK code and simulated with the DINA code. The codes have similar models of the CS and PF coils, coil power supplies and 2D models of the vacuum vessel (equivalent to the 3D model for axisymmetric components of the magnetic field produced by eddy currents induced in the vacuum vessel). The codes take into account magnetic fields produced in the breakdown region by magnetized ferromagnetic elements of the tokamak building (e.g. steel rebars) calculated using a complete 3D Magnetic Model of the Tokamak Complex MMTC-2.2. The magnetized ferromagnetic elements of the building produce at First Plasma operation about 100 G of vertical magnetic field opposite to the direction of the "Shafranov" field.

The PF scenario data obtained in the TRANSMAK code (the resistances for Switching Network Units (CS coils, PF1 and PF6), 11 waveforms of the pre-programmed voltages of CS and PF coil converters and 11 waveforms of the target currents in the CS and PF coils) were used in DINA simulations of the scenarios with free boundary plasma equilibria. The feedback control of plasma current and position was not used in the scenario simulations. The DINA code comprises a 2D free boundary plasma equilibrium solver (the first free boundary plasma equilibrium calculated with the DINA code corresponds to the plasma current 0.1 MA), 1D model describing diffusion of the poloidal magnetic flux and 0D plasma transport model (similar to that in SCENPLNT and TRANSMAK).

Two sets of the First Plasma scenarios were designed using the TRANSMAK code and simulated with the DINA code. In the design of the 1st set of scenarios, the goal was the formation at the gas breakdown of a large area with the poloidal magnetic field, B, less than 20 G. Such a configuration with a wide magnetic null is preferable for Ohmic breakdown. An example of a DINA simulation of the First Plasma scenario with a prefill gas pressure p = 0.4 mPa is illustrated in Figs. 2 and 3. The magnetic configuration obtained at the gas breakdown (t = 0.7 s) is illustrated in Figs. 2a and 2b. Fig. 2a shows the lines of constant value of the poloidal magnetic field and Fig. 2b shows the lines of constant value of the poloidal magnetic flux. The magnetic field in the breakdown region (shown by the black dashed circle with the radius 1.6 m) is less than 20 G. The area with B < 20 G is bounded in Fig. 2a by the green line. In this simulation, the first free-boundary plasma equilibrium is calculated at I_p = 0.1 MA (t = 0.85 s). As shown in Fig. 2c, at this time the plasma has a circular cross section. At t = 1.8 s

(Fig. 2d), when the plasma current reaches I_p = 0.56 MA, the voltages of the CS, PF converters are set to zero (active protection of the vacuum vessel housings), but the Switching Network Units continue operation.

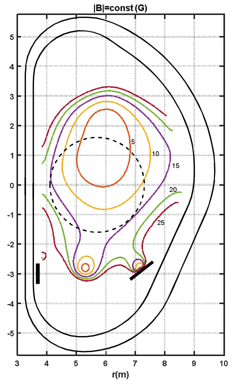

Fig. 2a: Lines $B = const$ at t = 0.7 s (*breakdown*) B = 5, 10,15, 20, 25 G

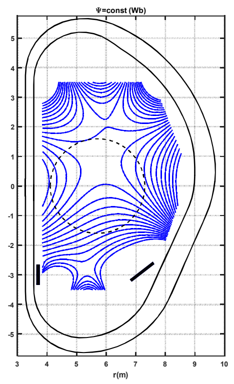

Fig. 2b: Lines $\Psi = const$ at t = 0.7 s (*breakdown*)

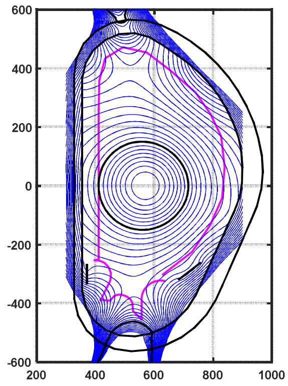

Fig. 2c: Lines $\Psi = const$ at t = 0.85 s, I_p = 0.1 MA (*first free-boundary plasma equilibrium*)

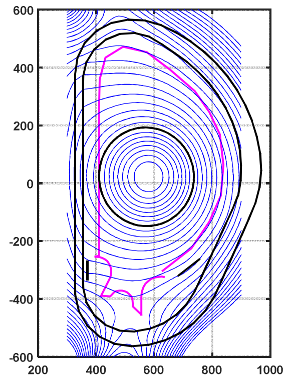

Fig. 2d: Lines $\Psi = const$ at t = 1.8 s, I_p = 0.56 MA (*when voltages of CS, PF converters are set to zero*)

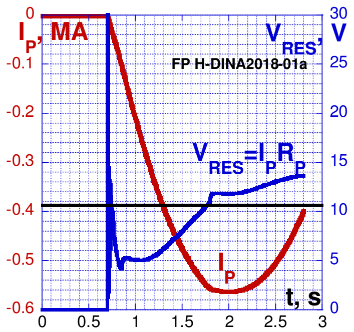

Fig. 3a: Plasma current (red) and resistive loop voltage (blue) (black line shows 10.6 V)

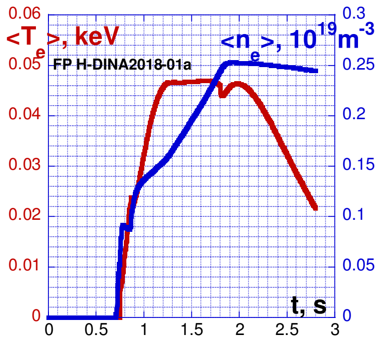

Fig. 3b: Electron temperature (red) and density (blue)

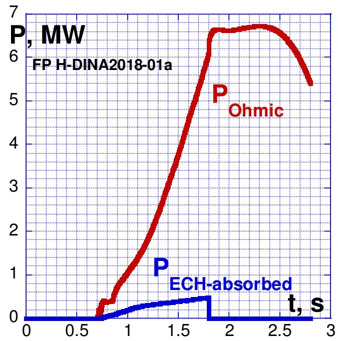

Fig. 3c: Power of Ohmic heating (red) and power of ECH absorbed in plasma (blue)

Figs. 3 show waveforms of plasma parameters obtained in this DINA simulation. The plasma current and resistive loop voltage are shown in Fig. 3a. One can see that due to an increase of Fe impurity, at $t \approx$ 1.8 s the resistive voltage exceeds 10.6 V produced by the PF system and the plasma current starts to decrease. Moreover, at this time, the coil converter voltages are set to zero. The electron density and temperature are shown in Fig. 3b. Fig. 3c shows waveforms of the Ohmic power and the ECH power absorbed in the plasma (assuming 2nd harmonic resonance and a single pass of the ECH beam).

In the design of the 2nd set of First Plasma scenarios, the goal was formation at the gas breakdown in the breakdown region with a small vertical magnetic field of a given value. In the scenarios designed with the TRANSMAK code and simulated with the DINA code, this was 15 G and 25 G, corresponding to the "Shafranov" field of plasmas with the currents 0.03 MA and 0.05 MA, respectively. Such magnetic configurations may be preferable for plasma initiation with ECH assist.

4. Formation of closed magnetic surfaces

An assessment of the critical value of the plasma current density required for formation of closed magnetic surfaces around the point with a "magnetic null" at gas breakdown was performed analytically based on a quasi-cylindrical approximation ($\rho << R_0$) using quasi-cylindrical co-ordinates (ρ, ω, ζ) in the area of the magnetic field null, $B(r = R_0, z = Z_0) = 0$ with the axis ζ passing through the "magnetic null" point in the toroidal direction. It was shown that the critical value of plasma current density required for starting formation of closed magnetic surfaces around the point with a "magnetic null" can be assessed as $j_{cr} \approx (2/\mu_0)[B_2(\rho)/\rho]$, where function $B_2(\rho)$ is the amplitude of the 2nd harmonic of the magnetic field in the Fourier expansion on the surface $\rho = const$:

$$B_\omega^{(2)}(\rho,\omega) = B_2(\rho) Sin(2\omega + \gamma_2).$$

In scenarios designed with the new version of the TRANSMAK code using, at the breakdown, the condition $B_2(\rho)/\rho \approx 0$, one can get a "perfect" magnetic configuration characterised by one "magnetic null" in a given point ($r = R_0$, $z = Z_0$) with 6 "petals" of the poloidal magnetic flux going out of the "magnetic null". In this case, the formation of closed magnetic surfaces starts from the "magnetic null" point at a very low ionization fraction and plasma current density. Moreover, the shape of the lines bounding areas with $B < 5$ G and $B < 10$ G are close to circular and these areas occupy significant fraction of the vacuum vessel.

However, in simulations with other codes of PF system operation designed starting with the TRANSMAK code, the original "perfect" breakdown magnetic configuration (obtained with TRANSMAK), having a single "magnetic null" with $B_2(\rho)/\rho = 0$ and 6 "petals", can be degraded even due to apparently insignificant differences in the codes leading to a small difference in the magnetic field calculated with these codes. In particular, a difference in the magnetic field of about 1 G in the magnetic configuration obtained with the DINA code in the simulations of the PF system operation designed with the TRANSMAK code, assuming $B_2(\rho)/\rho = 0$ (breakdown magnetic configuration with one "magnetic nulls" and 6 "petals"), leads to a breakdown magnetic configuration with two "magnetic nulls" and 4 "petals" going out of each "magnetic null". As a consequence, the critical value of plasma current density increases to ≈300 Am^{-2}, which corresponds to the critical value of the ionization fraction of ≈ 0.2%. Taking into account, that an error in the magnetic field of about 1 G is a very small error, it seems unlikely to experimentally achieve a magnetic configuration with the critical value of the ionization fraction < 0.2%. However the condition $B_2(\rho)/\rho \approx 0$ in "magnetic null" with a given location (e.g. R_0 = 5.41 m - location of the EC resonance and Z_0 = 0 - the midplane of CS) is a good target for design of PF system operation using a detailed electromagnetic model of the tokamak implemented in the TRANSMAK code.

5. Conclusion

The paper presents progress in simulation of ITER First Plasma operation since it was reported in [3]. In particular, studies performed with a 0D plasma transport model SCENPLINT have shown that due to several deteriorating plasma initiation factors: 1) a large volume of the vacuum vessel (1700 m^{-3}), 2) a low value of the toroidal electric field (0.3 Vm^{-1}), 3) a high Z limiter (Fe), 4) only one pass through the breakdown region of the ECH beam and 5) EC resonance on the 2nd harmonic (the 1st harmonic is much more efficient), the range of prefill gas pressure, p, required for First Plasma initiation is very narrow: ≈0.3 mPa < p < ≈0.7 mPa. The gas pressure lower limit, ≈ 0.3 mPa, is set by the generation of runaway electrons. The gas pressure upper limit, ≈0.7 mPa, is set by insufficient ionization.

Two sets of First Plasma scenarios were designed using the TRANSMAK code and simulated with the DINA code. In the design of the 1st set of scenarios, the goal was formation at the gas breakdown with a large area with the poloidal magnetic field less than 20 G. Such a "wide null" magnetic configuration is preferable for the Ohmic gas breakdown. In the design of the 2nd set of scenarios the goal was formation at the gas breakdown in the breakdown region with a small vertical magnetic field of a given value. Such magnetic configurations may be preferable for plasma initiation with ECRF assist.

The condition $B_2(\rho)/\rho \approx 0$ in a given location (e.g. R_0 = 5.41 m - location of the EC resonance and Z_0 = 0 - the midplane of CS) is a good target for design of PF system operation using a detailed electromagnetic model of the tokamak (e.g. the TRANSMAK code). This assures the start of formation of closed magnetic surfaces at low values of the ionisation fraction and plasma current density and the area with $B < 10$ G will occupy a significant fraction of the vacuum vessel.

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