Analysis of discharge scenarios in the T-15 tokamak

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Abstract. Currently, all of the main elements of the T-15 design have acquired their specifics, and, therefore, it is possible to conduct a sufficiently detailed analysis of future experiments. In this paper, we simulated the stage of current increase and the beginning of transition to a configuration with a divertor. We were interested in the degree of correlation between the scenario calculations, which were carried out using various numerical codes, the existence or absence of the problem with vertical plasma instability at this stage, and the accuracy of restoration of the plasma boundary, which depends on the error of magnetic sensors. As a result of calculations, it was possible to show that the stage of discharge, which was considered by us, is quite real from the point of view of its realization.

1. Introduction
The current construction of the T-15 tokamak makes urgent the task of analyzing the basic scenarios of discharge, which are supposed to be performed at this facility. The analysis of discharges at the T-15 installation at the stationary stage was carried out in [1, 2]. It was shown that such states can be supported by feedbacks. It was also shown that the magnetic diagnostic system can restore the plasma boundary with a specified accuracy, if the measurement error does not exceed 1–3%.

Meanwhile, the analysis of stationary states alone is inadequate. An example of an "unsuccessful" (unrealizable) scenario is given in [3], during which, because of an early stretching of the plasma pinch, a configuration appeared, whose vertical instability could not be suppressed by the feedback system.

Currently, all of the main elements of the T-15 design have acquired their specifics [4], and, therefore, it is possible to conduct a fairly realistic analysis of the stages of current increase and exit to the stationary stage during a discharge at the T-15 facility. The purpose of this work was to carry out this analysis. The stage of current increase and the beginning of transition to a configuration with a divertor was chosen for the analysis. For the first time, this analysis was carried out in [7], and the calculations were conducted using the widely known DINA code [8–9]. Currently, a new open-access computing resource (nfusion.cs.msu.ru), which integrated the TOKSCEN (equilibrium, vertical stability and evolution of plasma) [5] and RPB (restoration of the plasma boundary) [6] modules, was developed by a group of researchers from the Moscow State University and the IAE of the Republic of Kazakhstan. The purpose of this work was to perform a detailed analysis of the stage of current increase in the T-15 installation. We were interested in the following questions:
1) Comparison of the calculation results of the control points of the scenario, which was carried out according to the DINA and TOKSCEN codes;
2) Analysis of vertical plasma instability at the studied stage of discharge;
3) Restoration of the plasma boundary error as a function of the sensor error in the magnetic field measurements.

As a result of the calculations, it was possible to show that the stage of discharge considered by us is real from the point of view of its realization.

2. Results of the calculations
We analyzed the stage of current increase and pulling of the plasma column in vertical direction during the evolution of discharge in T-15 (discharge time from 0.7 to 1.2 sec) [7]. Several moments of time were selected within this interval, and each one was determined via the following: 1) the degree of compliance for the two different DINA and TOKSCEN codes; 2) the possibility of suppressing the vertical instability of the plasma; and 3) the accuracy of determining its boundary, taking into account the error in the signals on the sensors.

Figures 1–3(a) consistently represent the discharge moments t = 0.7, 1.0 and 1.19 s. It is important to note that the degree of correlation between the calculation results from the DINA and TOKSCEN codes is very good. There is a coincidence of up to three significant figures, both in magnitude of the currents and in terms of the geometric characteristic of the plasma pinch. Figures 1(b) and 3(b) show in different colors the accuracy of the boundary restoration and the separatrix with a relative error of signals at the sensors equal to 1%. A system of 36 two-component field sensors was used. It can be seen that with an error level of less than 1%, the error of determining the plasma boundary is not more than 2 cm, which is acceptable. However, an increase in the measurement error of the field to 3% leads to a serious deterioration in the determination of the accuracy of the boundary to a value of 3.5 cm, which is an unacceptable value [Fig.2(b)]. To maintain an acceptable accuracy of 2 cm, it is necessary to increase the number of magnetic sensors to 44. Note that the position of the “whiskers” of the separatrix and the x-point itself are controlled at a much higher accuracy – approximately 2.5 mm. This ensures the effective control of the divertor performance. As for the vertical instability, for the 0.7 and 1.0 s moments of time, it is absent, which is explained by the small ellipticity of the pinch cross section. Only at time t = 1.19 s, there is an instability with a small increment equal to 1.554 s⁻¹ (τ = 643.394 ms), which can be easily suppressed by the feedback.

3. Conclusion
As a result of calculations, it was possible to show that the stage of discharge, which is considered by us, is real from the point of view of its realization. Specifically:

1) the equilibrium calculations performed using two different DINA and TOKSCEN codes, coincided in both geometric characteristics and holding currents up to the third significant digit;
2) the vertical instability of plasma at this stage of the scenario is either completely absent or its increment reaches a non-dangerous value of the order of 1.5 s⁻¹, which is easily suppressed by the feedback. This result, unlike the “unfortunate” scenario [3], is explained by the fact that vertical pulling of the plasma cord starts to occur at the time when the current in the plasma reaches a significant value of approximately half of the maximum possible value, and the plasma fills a significant part of the chamber [Fig. 1(a)].

3) the plasma boundary at a given stage of discharge is controlled with an acceptable accuracy of less than 2 cm, provided that the relative error in determining the magnetic field of the sensors corresponds to the declared nominal value (1%). However, the error in determining the boundary becomes critically large (approximately 3.5 cm), if it turns out that the error in determining the fields by the sensors is higher than approximately 3%. The performed calculations show that the stage of discharge considered by us is realistic from the point of view of its realization.
Figure 1. (a) Stage of current rise in the T-15 installation. The moment of time $t = 0.7$ s, total plasma current $I_p = 0.91$ MA, large radius $R_{95} = 1.49$ m, small radius $a = 0.60$ m, ellipticity of the plasma column cross section $k = 1.17$, triangularity $\Delta = 0.11$, and poloidal beta $\beta_p = 0.1$. (b) Reconstruction of the plasma boundary (red and blue lines) and separatrix (green and yellow lines) with 36 two-component magnetic field sensors (black squares), the relative error of measurements is 1%.

Figure 2. (a) Magnetic configuration of T-15 at the moment of time $t = 1.0$ s, $I_p = 1.36$ MA, $R_{95} = 1.463$ m, $a = 0.68$ m, $k = 1.25$, $\Delta = 0.1$, $\beta_p = 0.14$. (b) The exact and reconstructed
boundary of the plasma (blue and red lines), and the exact and reconstructed separatrix (green and purple lines) at the same time (measurement error 3%), 36 two-component magnetic field sensors (black squares).

**Figure 3.** (a) Magnetic configuration of T-15 at the moment of time $t = 1.19 \text{ s}$, $I_p = 1.58 \text{ MA}$, $R_{\text{mid}} = 1.416 \text{ m}$, $a = 0.63 \text{ m}$, $k = 1.48$, $\Delta = 0.11$, $\beta_p = 0.13$. (b) The exact and reconstructed boundary of the plasma (separatrix – red and blue lines) at the same time, the relative level of measurement error of 1%, 36 two-component magnetic field sensors (black squares).

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