Measurements of the plasma parameters at the edge of the FT-2 tokamak and comparison with the gyro-kinetic model

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Abstract. Diagnostics of a plasma edge is an extremely important field of tokamak physics because this region determines the plasma-surface interaction. In the paper the plasma density, electron temperature and radial electric field at the plasma edge of the FT-2 tokamak are analyzed using the results of probe measurements. The measurements were performed in the experiments conducted with a plasma pinch being in a symmetrical vertical position and were compared with the results derived by the ELMFIRE code simulations to correct the model calculations. The experimental observations are shown to be in a reasonable agreement with the gyro-kinetic model predictions.

1. Introduction
The edge plasma and the phenomena occurring there are particularly important for thermonuclear fusion. The energy from the main containment volume enters the plasma edge, determining the plasma – surface interaction which, in turn, determines impurity transport. A substantial anomalous transport at the plasma edge is associated with fluctuations of plasma parameters (density, electron temperature, potential). This process has an impact on the formation of edge transport barriers and the transition to improved containment regimes. The outer spatial domain (scrape-off layer, SOL) outside the last closed magnetic surface (LCFS) presents known difficulties in diagnosing and interpreting experimental data. Complete «mapping» of this area requires great effort and is usually difficult in large-scale toroidal devices. At the same time, a lack of understanding of these anomalous processes at the plasma edge is a serious obstacle to the controlled fusion realization [1].

The aim of this work was to obtain experimental data on the edge plasma parameters of the FT-2 tokamak (Ioffe Institute) and to compare the measured values with the simulation results derived by the ELMFIRE gyrokinetic code [2]. The code was developed by the Aalto University School of Science in cooperation with the Technical Research Centre VTT of Finland for investigation of transport phenomena in tokamak. The code was created in close cooperation with the tokamak group FT-2, whose parameters in particular the relatively small scales (large radius \( R_0 = 0.55 \) m, radius of poloidal diaphragm \( a = 0.078 \) m) and high level of fluctuations are well suited for modelling.
Computational physics has become an indispensable tool in fusion research, as experimentation is costly, preparation takes a lot of time, and measurements of some important phenomena and quantities are difficult. To create an adequate model, however, it is necessary to verify if the data obtained during the machine simulation process correspond to the actual course of events.

2. Experimental setup
Measurements of the edge plasma parameters were carried out with the aid of movable five-electrode Langmuir probes. The probe measurement method \[3\] applied at FT-2 makes it possible to determine the temporal evolution of local values of the plasma potential, electron density and temperature, as well as the two-dimensional (poloidal) density of particle flow, related to the $E \times B$ drift.

The gyrokinetic code deals with a plasma configuration model which is arranged strictly symmetrically in the internal volume of the tokamak chamber when the position of the LCFS coincides with the edge of the circular poloidal diaphragm. In order to obtain experimental data in the symmetrical position of a plasma pinch for code testing, it was necessary to have the possibility of probe measurements at the top and bottom of the SOL. Thus, it became necessary to install the probe in the upper port and to equip it with a precision displacement system with scale devices. In the course of the work, a probe device was constructed, calculations were made, and a table was drawn up for the conversion of the scale readings into the coordinates of the probe position within the tokamak chamber. The upper probe makes it possible to get the measurements in the shadow of the limiter within the limits of the poloidal angle $\Theta$ from $90^\circ$ to $160^\circ$. The angle $\Theta$ is calculated from the outer equatorial point in the upper direction. The lower probe spans the $\Theta$ range from $190^\circ$ to $340^\circ$. The results of the measurements were processed by computer programs developed during the work.

It was necessary to perform probe measurements with the plasma pinch being in a symmetrical vertical position to compare the results of the ELMFIRE simulation with the experimental data and to correct the model calculations. To this end the Ohmic Heating discharge in hydrogen was studied at the following values of the main parameters: $B_t = 22$ kGs, $I_p = 22$ kA and quasi-stationary interval of the discharge $\Delta t = 40$ ms. These parameters are close to the ELMFIRE calculation input.

The central position of the plasma pinch vertically was provided by the system of maintaining the plasma balance by programmable changes in control magnetic fields. During the pulse of the discharge current a small movement of the plasma column along the vertical axis was observed. At the same time, the cord occupied the central position in the time interval of $\sim 5$ ms in the vicinity of the twenty-seventh millisecond operating pulse of the unit.

The vertical profiles of both the density and the electron temperature obtained by a laser Thomson scattering diagnostic during this interval are symmetrical with good accuracy with respect to the vertical count (y-axis). The electron temperature in the central discharge area was $T_e \approx 400$ eV. The electron density was $n_e \approx 3.5 \cdot 10^{13}$ cm$^{-3}$ in the central discharge region. A good symmetry has also been confirmed by the measurements using the UH enhanced scattering diagnostics \[4\].

3. Experimental data
The experimental code testing is carried out in the upper and lower parts of the vacuum chamber. The probe measurements were performed at poloidal angles $\Theta = 110^\circ$ (upper probe) and $\Theta = 250^\circ$ (lower probe) on the high-field side (HFS), and at $\Theta = 290^\circ$ (lower probe) on the low-field side (LFS). The angles are measured from the outer equatorial point $\Theta = 0^\circ$ (LFS) in the upper direction (counterclockwise direction).
Figure 1 shows the radial profiles of the electron temperature ($T_e$), plasma density ($n$) and radial electric field ($E_r$). In addition to the experimental data, this figure represents the results obtained by using the ELMFIRE code [4],[5].

It can be seen that the local plasma density for all three poloidal angles are slightly higher than the calculated values. The best match is at the top of the tokamak chamber at $\Theta = 110^\circ$ (HFS). However, the discrepancy is not critical.

The experimental values of the electron temperature match the simulation results pretty well, except for the case of $\Theta = 290^\circ$ (LFS). The results of model calculations are slightly higher than the experimental value at this poloidal angle.

The value of the radial electric field was calculated by approximating the experimental profiles $T_e(r)$ with the functional dependency and measured floating potential values ($\varphi_f$) according to the expression: $E_r = -\text{grad}_r(\varphi_f + 3T_e/e)$. As shown in figure 1, the radial electric field profiles are non-monotonic, which corresponds to theoretical assumptions. Comparing the experimental data with the modelling results, we can conclude that the above procedure for obtaining the experimental radial electric field results in increased measurement error. The behaviour of experimental curves is similar to the simulation results, as shown in Figure 1. The difference in radius values at which the field direction changes the sign is at most 1 mm at $\Theta = 110^\circ$ and 250$^\circ$ (HFS).

Comparing the results of the gyro-kinetic simulation and the experiment at the boundary of the limiter, one can immediately note that the density values are roughly the same and the electron temperature values by a factor of 2. The experimental results and the ones predicted by the model coincide fairly well. The main thing is that the temperature at the top of the chamber is higher than at the bottom. In its turn, the density is roughly the same everywhere.

The discrepancy between the measurements and the model calculations may be related to the following circumstances. First, in the described experiments, the profiles of $T_e$ and $n_e$ in the
plasma core do not fully correspond to the input data of the calculations. Second, the position of the limiters in the model differs from the real one: the code assumes that the two limiters are arranged symmetrically one to the other, while the tokamak FT-2 limiters are shifted in the toroidal direction at an angle of 90°. Finally, as already mentioned, the deficiencies in the reliable reproduction of the experimental equilibrium have been identified, which requires the source and run-off model refinements in the SOL, such as recycling and charge exchange processes.

4. Conclusion
The experimental results and the results of the gyro-kinetic simulations are well correlated, which confirms the correctness of the model. In a real toroidal device, some parameters in the inter layer plasma are physically impossible to measure and can be recognized by this code. The obtained results will contribute to the further development of the ELMFIRE code used for modelling the heat transport features in high-temperature plasma.

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