Effect of the toroidal magnetic field the on energy and fast particle confinement in the Globus-M spherical tokamak

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Abstract. The experiments with auxiliary heating by neutral beam injection (NBI) were carried out before the spherical tokamak Globus-M was upgraded to Globus-M2. The aim of the experiments was to determine the dependence of the confinement time on toroidal magnetic field. The total stored energy was obtained by diamagnetic loops, and verified with ASTRA modelling based on kinetic measurements. The absorbed heating power was estimated using 3D fast ion tracking modeling. The obtained dependence of the energy confinement time is similar to the MAST and NSTX results but contradicts the conventional IPB98(y,2) scaling. The toroidal Alfvén eigenmodes study was performed in a set of discharges with NBI at the early stage of the discharge. The experiments have shown that fast particle losses decrease with the increase of the toroidal magnetic field and plasma current.

1. Introduction
One of the main reasons for the energy and fast particle losses in spherical tokamaks is a low toroidal magnetic field. Therefore the toroidal magnetic field will be increased by 2.5 times (from 0.4 T to 1 T) in the upcoming Globus-M2 machine [1]. Improvement in fast particle confinement is therefore expected. Toroidal magnetic field in the Globus-M [2] tokamak was increased up to 0.5 T during the last experimental campaign and a series of experiments were performed with auxiliary heating by means of neutral beam injection (NBI). The total plasma stored energy and the energy confinement time were estimated using kinetic and magnetic measurements. A significant increase of the plasma total stored energy was observed with the increasing magnetic field, while heating power wasn’t change significantly. This phenomenon is associated mainly with the confinement time rise. The fast particle confinement was also improved due to decrease of the orbital losses and losses due to MHD instabilities, including toroidal Alfvén eigenmodes (TAE).

2. Thermal energy confinement time dependence on the toroidal magnetic field.
The experiments were carried out for the values of the toroidal magnetic field $B_T = 0.4$ T and $B_T = 0.5$ T, while the plasma current $I_p = 200$ kA remains at the same level. The ohmic heating power was about ~ 0.23 MW. The auxiliary heating was performed using the deuterium beam (beam energy $E_b = 26$ keV, beam power $P_b = 0.7$ MW), that was injected into deuterium plasma at the steady state stage of the discharge during the current flat-top phase. The beam duration ($t_{beam} = 40$ ms) significantly exceeded the typical value of the energy confinement time $\tau_E = 3\div5$ ms. The line average electron density was changed for different discharges in the range of $1.5\cdot10^{19}$ m$^{-3}$. 

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Electron temperature and density profiles were measured by the Thomson scattering (TS) diagnostics [3], the line average density was monitored by the microwave interferometer. Investigation of the ion component of the plasma was performed with the help of the two neutral particle analyzers that measured charge exchange atomic fluxes outgoing from the plasma column in tangential and transversal to toroidal magnetic field directions. This data was used to estimate the fast particle losses level, ion temperature, ion composition and the quantity of the absorbed beam power.

To determine the energy confinement time plasma total stored energy was estimated using two different approaches. The first approach is based on the diamagnetic measurements, the second one is the integration of the kinetic profiles using ASTRA modelling [4] and Zero-dimensional code [5]. Figure 1 shows the energy confinement time $\tau_E$ as a function of the average electron density $<n_e>$. The significant difference in energy confinement time for different magnetic fields appears for the densities higher than $3 \cdot 10^{19} \text{m}^{-3}$. The dependence of the confinement time on toroidal magnetic field for the Globus-M tokamak was calculated for this range as $\tau_E \sim B^{0.9\pm0.2}$. This result corresponds well to preliminary analysis presented in [6].

![Figure 1. The energy confinement time dependence on the line average electron density. Comparison of the different energy confinement time estimation approaches (ASTRA code, zero-dimension code and diamagnetic measurements) for the different experimental conditions: the same plasma current (200 kA) and various toroidal magnetic fields (0.4 T and 0.5 T).](image)

ASTRA simulations were used to determine thermal diffusivity coefficients for ions and electrons, for plasma with different densities. The modeling was performed for the quasi-stationary stage of the discharges using the following assumptions. The ion temperature profile was calculated assuming neoclassical transport coefficients that were calculated with the help of NCLASS transport code [7]. This approach is valid, since the recent experiments carried out on Globus-M demonstrated neoclassical behavior of the ion transport [8,9] like in other spherical tokamaks [10,11]. The magnetic equilibrium was reconstructed using the EFIT code [12]. The effective plasma charge ($Z_{eff}$) was set as a constant along the minor radius. The $Z_{eff}$ value was estimated by matching the calculated loop voltage with the experimental one. Carbon was assumed as the main impurity. The profiles of the neutral beam absorbed power were determined by a standard block of the ASTRA code. Additional correction for the first orbit losses of the fast particles was made using the three-dimensional modelling algorithm [13].

The electron heat diffusivity profiles were calculated using TS profiles. The neoclassical ion heat diffusivity varies slightly with density, while the electron heat diffusivity decreases dramatically.

The dependence of the confinement time on toroidal magnetic field was studied for the same plasma current and for the different densities $<n_e> \sim 1.5 - 4.2 \cdot 10^{19} \text{m}^{-3}$. It was found that the influence of the magnetic field on energy confinement is considerable in Globus-M. However, the ITER scaling predicts [14] weak dependence of the confinement time on toroidal magnetic field ($\tau_E \sim B^{0.15}$). It is opposite to well-known spherical tokamak experiments [15,16] (where are $\tau_E \sim B^{1.4}$ in MAST and $\tau_E \sim B^{1.08}$ in NSTX). The energy confinement time that was calculated by IPB98(y2) scaling shows that is rather H-factor weak 0.7-0.9 for the range of densities $<n_e> \sim 2 - 3.5 \cdot 10^{19} \text{m}^{-3}$. 


3. Toroidal Alfvén Eigenmodes

Instabilities, identified as toroidal Alfvén eigenmodes, were found in the experiments with NBI in the early stage of the discharges [17]. To study dependence of the fast particle losses induced by TAE on the toroidal magnetic field value, the experiments with the increased magnetic field (0.5 T) were carried out.

The results of the experiments with the increased toroidal magnetic field and plasma current were compared with the previous experiments (0.4 T, 200 kA). Figure 2 demonstrates MHD signal (fig. 2a) and the NPA flux (fig. 2b) for two cases: 0.4 T, 200 kA – red lines and 0.5 T, 250 kA – green lines. Correlation between the TAE burst and the NPA flux drops is marked by the dashed lines. From these figures one can see that at the increased magnetic field and plasma current the bursts of the Alfvén modes become more frequent, and the levels of fast particle losses during the burst decrease. The increase in the frequency of the flushes is probably associated with the better accumulation of the fast particles due to the lower classical and TAE induced losses.

In figure 2 (c) the dependence of the drop in the NPA flux (energy of particles is 28.5 keV) on the amplitude of the Alfvén mode is presented. The figure demonstrates that increase of the magnetic field and plasma current leads to decrease of the fast particle losses induced by TAE.

4. Conclusions

The energy confinement time increases with toroidal magnetic field growth, especially for high densities. Results of the diamagnetic measurements, zero-dimension code and ASTRA code calculations are in a good agreement. With the rise of electron density the H-factor increases approaching IPB98(y,2) scaling value. The strong dependence of the energy confinement time on the magnetic field ($\tau_E \sim B^{0.9\pm0.2}$) found on Globus-M, is in a good agreement with other spherical tokamaks.

The experiments demonstrate that increase of the magnetic field and plasma current leads to decrease of the fast particle losses induced by TAE while the modes became more frequent. The increase in the mode frequency is probably associated with the better accumulation of fast particles due to lower classical and TAE losses.
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