Effect of increase in the toroidal magnetic field on plasma heating and confinement in the Globus-M tokamak discharges with neutral beam injection

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Abstract. In the course of modernization of the Globus-M spherical tokamak, the experiments at the increased toroidal magnetic field (from 0.4 to 0.5 T) and with the additional heating by neutral beam injection were carried out. The numerical simulations were performed using the ASTRA transport code. A considerable increase in the absorbed neutral beam power as well as in the energy lifetime and total energy content was achieved due to the increase in the toroidal magnetic field and plasma current.

1. Introduction
The authors have more than once noted that the low toroidal magnetic field (0.4 T) in the Globus-M spherical tokamak [4] is one of the main reasons for limiting the further improvement of plasma parameters [1–3]. The low magnetic field also reduces the possibilities of using the additional plasma heating and current drive techniques. In the upgraded Globus-M2 facility, the toroidal magnetic field will be increased up to 1.0 T [5]. A new electromagnetic system and power supplies were developed and manufactured.

During the last experimental campaign, all new power supplies were tested in experiments at the Globus-M tokamak. They were connected to the coils of the existing electromagnetic system. The variation range of feeding currents was increased by 25%. Under these conditions, a series of experiments on plasma heating by the neutral beam injection (NBI heating) was carried out. These experiments were aimed to study the effect of the toroidal magnetic field and plasma current on the confinement of fast ions appearing in the course of the neutral beam injection as well as on the plasma confinement.

2. The results of experiments on plasma NBI heating
In the experiments, the toroidal magnetic field and plasma current varied in the ranges of 0.4–0.5 T and 200–250 kA, respectively. The deuterium beam (26 keV, 0.7 MW) was injected into deuterium plasma in the stationary stage of the discharge (at 160 ms). The beam duration (40 ms) manyfold exceeded the typical energy lifetime $\tau_E$. During the beam injection phase, the mean electron density was maintained at the level of $3-4 \times 10^{19} \text{ m}^{-3}$.

Figure 1 shows time evolution of the plasma parameters for three shots with different toroidal magnetic fields and plasma currents. The shot #36594 is a typical of the Globus-M shot with the usual
mean density, plasma current of about 200 kA and the toroidal magnetic field of 0.4 T on the axis. In the shot #36610, the toroidal magnetic field was increased up to 0.5 T, the plasma current being the same. And in the shot #36618, the plasma current was increased up to 250 kA and the toroidal magnetic field remained 0.5 T. The electron temperature and density profiles were measured using the Thomson scattering diagnostics. The measured radial profiles of the electron temperature $T_{e,exp}$ for these three shots are shown in Figure 2 by black dots. The mean chord density was monitored by a microwave interferometer. The ion component of the plasma was studied by means of two neutral particle analyzers, which measured the fluxes of neutral atoms coming from plasma after the processes of charge exchange in collisions with ions. The analyzers were oriented in tangential and transversal to the beam line directions. These data were used to estimate the fast particle losses, the ion temperature, ion composition and the absorbed beam power. The total energy content of plasma was estimated from the diamagnetic measurements using the set of loops.

3. Description of the transport code

The ASTRA transport code [6] was used for processing of the experimental results. In simulations, we studied the thermal diffusivity coefficients, total plasma energy content and energy lifetime as functions of the toroidal magnetic field and plasma current.

The modeling was carried out in the quasi-stationary stage of discharge (~170 ms) under the following assumptions. Assuming the transport coefficients to be neoclassical, we calculated the ion temperature profiles using the NCLASS transport code [7]. As the boundary conditions for solving the balance equation using the ASTRA code, we used the parameters of the last closed magnetic surface, recovered using the EFIT code [8]. The effective plasma charge was assumed to be constant along the minor radius. The $Z_{eff}$ value was determined by comparing the estimated and measured loop voltages. Carbon was assumed to be the main impurity. The absorbed power of the neutral beam was calculated using a standard block of the ASTRA code [9]. The additional corrections to the absorbed power were made in order to take into account the fast particle losses from the first orbits. These losses were determined using the 3D modeling algorithm [3].
4. Discussion of the simulation results

The simulation results of the electron and ion temperatures as compared to the experimental data are shown in the Fig. 2. The figure demonstrates the considerable increase in the electron and ion temperatures with increasing both the toroidal magnetic field and plasma current. In each of the shots considered, the effective plasma charge was about 2.4–2.5. Table 1 shows the energy contents of plasma $W_{\text{ASTRA}}$ and $W_{\text{diam}}$ calculated using the ASTRA code and from data of the diamagnetic measurements, as well as the energy lifetimes $\tau_{E\text{ASTRA}}$ and $\tau_{E\text{IPB98(y,2)}}$ calculated using the ASTRA code and the scaling IPB98(y,2) [11]. Data on the total absorbed power, the absorbed power of the beam with allowance for the losses and the other integral characteristics of the discharges are also given in Table 1.

(a) $B_T = 0.4 \, T, I_p = 200 \, \text{kA}$  
(b) $B_T = 0.5 \, T, I_p = 200 \, \text{kA}$  
(c) $B_T = 0.5 \, T, I_p = 250 \, \text{kA}$

*Figure 2.* Electron (black) and ion (red) temperature profiles calculated and measured at 170th ms (lines and dots, respectively) for three shots with different toroidal magnetic fields and plasma currents.

Increase in the toroidal magnetic field by 25% at a fixed plasma current of 0.2 MA resulted in the rise of the total energy content by 30% which is confirmed by the diamagnetic measurements. In this case, the total absorbed power didn’t considerably change because the efficiency of fast ions confinement which determines power of additional heating better depends on the plasma current but not on the toroidal magnetic field [3]. Therefore, an increase in the energy content is a consequence of the improved confinement of thermal energy and exactly the electron energy confinement is improved at that (see Fig. 3 and Table 1). An increase in the plasma current up to 0.25 MA at the fixed magnetic field $B_T = 0.5 \, T$ results in the rise of the absorbed power by 20%, the total energy content and energy lifetime being increased by 40 and 20%, respectively (as compared to the typical discharge). Heat diffusivities for electrons and ions are presented in Figure 3. The electron heat diffusivity decreases both with the rising current $I_p$ and magnetic field $B_T$. The dependence of the confinement time on the plasma current and magnetic field was $\tau_{E} \sim B_{T}^{0.8 \pm 0.1} I_{p}^{0.8 \pm 0.1}$.

(a) $B_T = 0.4 \, T, I_p = 200 \, \text{kA}$  
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*Figure 3.* Heat diffusivities for electrons $\chi_e$ (black) and ions $\chi_i$ (red)
Table 1. Comparison between the calculated and measured plasma parameters for the different magnetic fields and plasma currents

| Discharge | #36594 | #36610 | #36618 |
|-----------|--------|--------|--------|
| Toroidal magnetic field, B_T, T | 0.4 | 0.5 | 0.5 |
| Plasma current, I_p, kA | 200 | 200 | 250 |
| Z_eff | 2.4 | 2.5 | 2.5 |
| Full absorbed power, P_{abs}, MW | 0.527 | 0.543 | 0.667 |
| NBI absorbed power, P_{nbi,abs} ,MW | 0.285 | 0.32 | 0.389 |
| W_{diam}, kJ | 1.7 | 2.38 | 3.42 |
| W_{fast}, kJ | 0.24 | 0.36 | 0.51 |
| W_{ASTRA}, kJ | 1.56 | 2.02 | 3.11 |
| \tau_{E,ASTRA}, ms | 3 | 3.7 | 4.7 |
| \tau_{E,IPB98(y,2)}, ms | 4.3 | 4.6 | 5.2 |
| H_{IPB98(y,2)} = \tau_{ASTRA}/\tau_{IPB98} | 0.7 | 0.8 | 0.9 |

The studies carried out at the MAST spherical tokamak [12] have shown that the dependence of the energy lifetime on the toroidal magnetic field is much more strong than that given in the scaling IPB98(y, 2), and at the same time the corresponding dependence on the current is linear. The similar dependence on the magnetic field was observed at the NSTX tokamak, however, the dependence on the plasma current is linear under conditions of boronization of the vacuum chamber walls performed after their cleaning by the glow discharge [13].

The experiments on the additional NBI plasma heating carried out at the Globus-M tokamak demonstrated that the dependences of energy lifetime on the toroidal magnetic field and on plasma current are close to linear at a moderate mean density of \( \sim 4 \cdot 10^{19} \text{ m}^{-3} \). This result is hopeful to expect the considerable improvement of the plasma parameters in the Globus-M2 spherical tokamak which will operate at the higher current \( I_p \) and toroidal magnetic field \( B_T \).

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