Toroidal magnetic field increase in the Globus-M spherical tokamak

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In the final Globus-M (R ≈ 0.36 m, a ≈ 0.24 m, k ≈ 1.8, δ ≤ 0.5) experimental campaign B_{tor} and I_p were increased by 25% up to 0.5 T and 250 kA respectively, expanding experimental parameters range and providing the possibility to test new Globus-M2 diagnostics and power supply system.

Deuterium plasma was studied. In the experiments with the additional heating 0.7 MW 26-28 keV D neutral beam injection (NBI) was applied. Electron density n_e and temperature T_e were measured using Thomson scattering system. Line integrated n_e was measured using microwave interferometer. Ion temperature T_i and plasma isotope composition were estimated using neutral particle analyzer NPA ACORD-12 [1]. Influence of the Alfvén eigenmodes on the fast ion loss and redistribution was estimated using NPA ACORD-24M, which observed plasma in the equatorial plane with the same impact parameter as NBI. Structure of the Alfvén eigenmodes was measured using 4 “fast” toroidal magnetic probes and 28 poloidal magnetic probes. Data, obtained with a new 1×24 SPD [2] linear array, combined with the data, provided by the 16×16 SPD matrix array was used for the plasma emissivity reconstruction. A new movable Langmuir probe, installed at the outer midplane, was used for the measurements of the T_e and n_e profiles in SOL. Neutron rate evolution was observed with the help of two corona neutron counters with a polyethylene moderator. Magnetic configuration was reconstructed by the EFIT code [3].

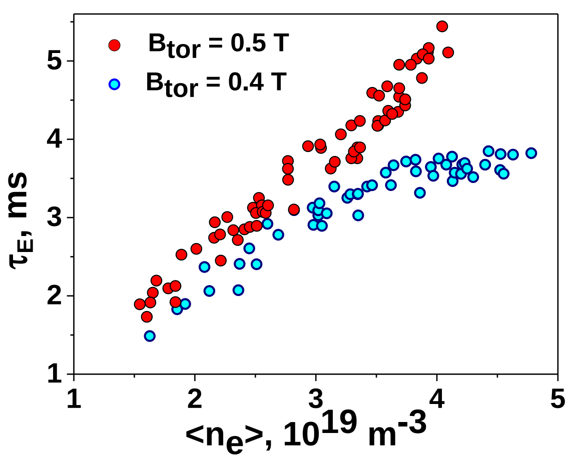

Fig. 1. Energy confinement time during D NBI into D plasma in I_p=0.2 MA discharges with the different toroidal magnetic field (B_{tor} = 0.4 T and B_{tor} = 0.5 T).

The dependence of energy confinement time τ_E on B_{tor} and n_e was studied in a set of NBI-heated discharges at fixed Ip = 0.2 MA. Fig.

1 represents the obtained dependence of τ_E on plasma density at different magnetic field values. It can be seen that energy confinement time in the experiments with the increased magnetic field is ~25% higher. The total stored energy was measured using the diamagnetic loop and verified by the zero-dimensional code that incorporates kinetic data. It should also be pointed out that the NBI absorbed power doesn't significantly increases at high field case, since the fast particle losses in Globus-M are mostly depend on I_p. The dependence of τ_E on B_{tor} was estimated as $\tau_E \sim B^{0.9\pm0.1}$.

The joint increase of B_{tor} and I_p by 25% has led to about 30% D-D beam-plasma neutron rate increase due to fast particle population growth. The main reason of fast ion content growth was T_e rise. It was observed experimentally and verified by NUBEAM [4] calculations that increase of T_e led to ~20% neutron rate growth. Another reason for fast ion population growth was first orbit losses decrease due to I_p rise. Full orbital modeling showed that I_p increase at fixed B_{tor} should result in 25% higher neutron rate mainly due to a first orbit losses fall. These estimations are higher, than experimentally observed neutron rate increase (~10%). Additional study is needed to reveal the reason of discrepancy. Finally, experiments showed, that influence of the sawtooth oscillations on the fast ion confinement and, hence, neutron rate, also decreases with the magnetic field and plasma current growth.

Toroidal Alfvén eigenmodes (TAE) were studied at increased B_{tor} and I_p. As compared to 0.4 T experiments, the mode character has changed: while in the experiments with B_{tor}=0.4 T the TAE bursts usually existed only in the early stage of the discharge, when there were no sawtooth oscillations, at B_{tor}=0.5 T these bursts became more frequent and often existed on the current plateau, sometimes in the presence of sawtooth oscillations. The main reason for that is more effective fast ion accumulation due to lower classical, sawtooth-induced and TAE-induced losses. The influence of TAEs on fast particle confinement became sufficiently weaker with the I_p rise and slightly weaker with B_{tor} rise. The strongest effect was reached at simultaneous increase of the B_{tor} and I_p

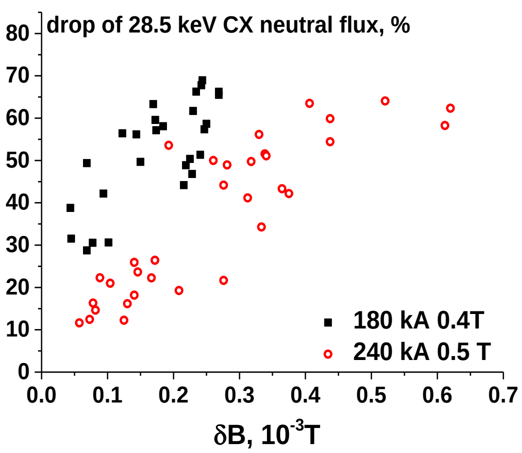

Fig. 2. Dependence of the CX neutral flux drop on the TAE amplitude at 0.4 T, 180 kA and 0.5 T, 240 kA.

up to 0.5 T and 240 kA respectively. The dependence of the charge exchange (CX) neutral flux drop on the TAE amplitude at different I_p and B_{tor} values is shown in Fig.2.

In the last experimental campaign, a new Langmuir probe was installed at the outer midplane of the machine. The probe has a nine-pin head and it is driven by a linear magnetic manipulator which provides the shot-to-shot radial displacement of the probe and its rotation around the central axis. Electron temperature and density profiles in SOL were measured in two series of deuterium discharges with lower single-null and close q_{95} values: #37068-37074 with B_{tor} = 0.4 T, Ip = 180 kA and #37062-37066 with B_{tor} = 0.5 T, I_p = 225 kA. The results were compared with Eich's scalings of 2011 [5] and 2013 [6]. Like in the previous experiments [7], derived values of λ_q are more close to Eich-2013 scaling. Earlier the λ_q dependence on plasma current [7] was updated using expanded database with plasma current values from 115 kA to 250 kA: $\lambda_q = I_p^{-1.3\pm0.2}$.

Plasma radiation losses on the Globus-M tokamak were investigated using diagnostics based on SPD photodiodes. The linear array was installed in the equatorial mid-plane of the tokamak and observed plasma in the poloidal cross-section. To determine plasma emissivity, a computer code for tomographic reconstruction procedure was developed. The reconstruction procedure involves solution of an ill-posed problem using Tikhonov regularization method [8]. The distribution of plasma emissivity, averaged over plasma magnetic surfaces (from low field side and high field side separately), for I_p=200 kA, B_{tor} = 0.4 T and I_p=250 kA, B_{tor} = 0.5 T OH discharges is shown in fig. 3. Plasma emissivity was lower in the discharges with the increased toroidal magnetic field. Lower radiation losses in plasma with higher B_{tor} have been found for a wide range of electron densities. Increase of electron temperature is the main reason of the reduction of radiation losses.

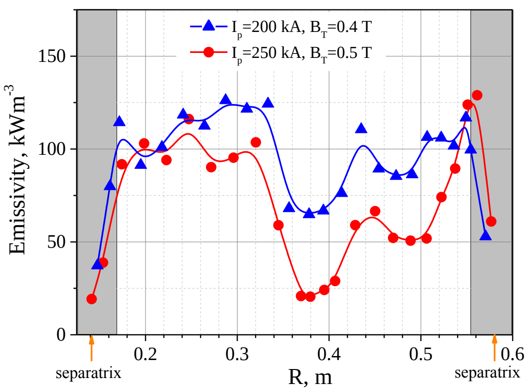

Fig. 3. Magnetic surface averaged emissivity profiles inside LCFS in the discharges with I_p=200 kA, B_{tor}=0.4 T and I_p=250 kA, B_{tor}=0.5 T for OH heated discharges, D plasmas.

In the final Globus-M experimental campaign B_{tor} and I_p were raised up to 0.5 T and 250 kA respectively. As a result an overall improvement in plasma confinement was observed. Beam-plasma neutron rate increased significantly at the same NBI power and energy. Decrease of classical, sawtooth-induced and TAE-induced fast ion losses as well as radiation losses was recorded. The growth of τ_E proportionally to the toroidal magnetic field was observed. Energy confinement time and power decay length scalings were acquired in the experiments. In addition two new diagnostics: SPD array and a new movable 9-pin head probe were for the first time used on Globus-M. After the successful experimental campaign Globus-M was disassembled. This year a new Globus-M2 ST with the same vacuum chamber, 2.5 times increased B_{tor} and I_p, and upgraded heating and a diagnostic systems was launched. A significant expansion of the experimental parameter range will provide an opportunity to get closer to the operating conditions of the compact fusion neutron sources (CFNS) and, hopefully, answer the question, if the pros of the ST configuration outweigh the cons when used as a basis for a CFNS. Full-scale experiments on the new Globus-M2 tokamak are scheduled for 2018.

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