The results of the first experimental campaign on the Globus-M2 spherical tokamak

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Introduction

Globus-M2 [1] is deeply upgraded version of the Globus-M tokamak [2] in which the vacuum vessel and the entire diagnostic complex are preserved, and a new electromagnetic system is significantly strengthened in order to withstand higher currents and, accordingly, increased mechanical loads. The tokamak was designed to reach the toroidal magnetic field as high as B_T =1 T and the plasma current I_p = 0.5 MA. The magnetic system provides operation in diverter single or double null configuration with the aspect ratio $A = R/a$ = 1.5, plasma minor radius a = 0.24 m, triangularity up to δ~0.5 and elongation up to κ~2.2. Currently 80% of highest magnetic field and plasma current value have been reached. So during the reported period the experiments were performed with the toroidal magnetic field up to 0.8 T and plasma current up to 0.4 MA. An overview of the results obtained on Globus-M2 since 2018, when the first plasma was obtained, is presented.

Energy Confinement

Previous research on the spherical tokamak Globus-M, as well as on MAST and NSTX, has shown strong dependence of the energy confinement time τ_E on the magnetic field and weak dependence on the plasma current [3], unlike the IPB98(y,2) scaling predictions for conventional tokamaks [4]. But all these experiments were carried out with $B_T \leq 0.55$ T. We have continued the experiments on Globus-M2 at higher magnetic field. The main parameters of shot #38835 with $B_T = 0.8$ T and $I_p = 0.4$ MA are shown in Fig.1. With the assistance of neutral beam (hydrogen, 26 keV, 0.85 MW) the electron and ion central plasma temperatures exceeded 1 keV at the central density as high as $1 \times 10^{20}\ \mathrm{m^{-3}}$. The thermal energy increased up to 10 kJ, which is nearly triple as high as in Globus-M ($B_T = 0.4$ T, $I_p = 0.2$ MA). The energy confinement time was obtained from the analysis for different combinations of plasma currents and magnetic fields. Triple increase of τ_E was recorded at twofold growth of B_T. The regression fit of the Globus-M/-M2 data for NBI H-mode discharges yields the following scaling for energy confinement time:

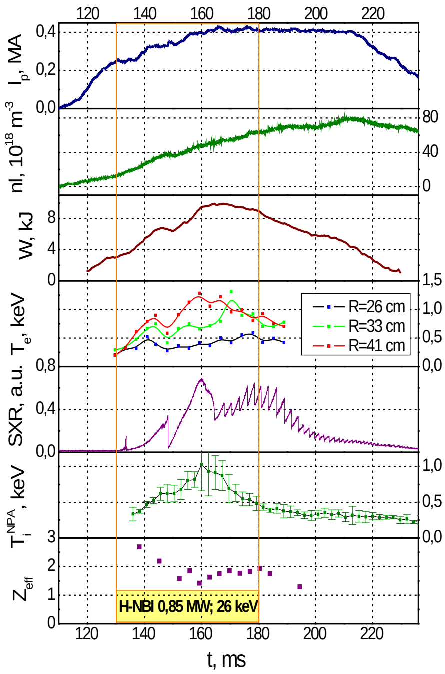

Fig.1 Plasma parameter waveforms for shot #38835 with $B_T = 0.8$ T and $I_p = 0.4$ MA, from top to bottom: plasma current, line density, plasma stored energy, electron temperature, SXR emission, ion temperature, plasma effective charge

$$\tau_E^{GLB} = 0.01\, I_p^{0.43\pm0.22}\, B_T^{1.19\pm0.1} P_{abs}^{-0.59\pm0.23} n_e^{0.58\pm0.1}$$

Here P_{abs} is the absorbed heating power and n_e is the line average density. The scaling confirms relatively weak τ_E dependence on I_p that emphasizes the major role of B_T on perpendicular heat transport in spherical tokamaks. Globus-M/-M2 scaling for normalized confinement time shows strong dependence on collisionality $B_T\, \tau_E \sim \nu^{*-0,74}$ unlike the scaling: $B_T \tau_E \sim \nu^{*-0,01}$ for high aspect ratio tokamaks.

Fast Particle Confinement

The enhancement of I_p and B_T led to better confinement of fast ions arising during the neutral beam injection. NUBEAM and full orbit modeling showed that at $B_T = 0.4$ T and $I_p = 0.2$ MA up to 90% of the injected beam power is lost, while at $B_T = 1$ T and $I_p = 0.5$ MA the losses become much smaller [5]. The experiment on Globus-M2 has confirmed the modeling results. Fast ion confinement improvement may be illustrated by

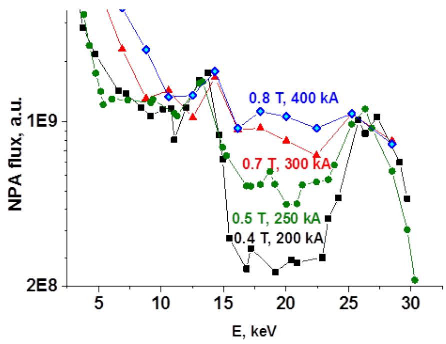

Fig.2 NPA flux measured in the NBI discharges (deuterium beam, 28 keV, 0.8 MW) with the different plasma current and toroidal magnetic field

Fig. 2, where charge exchange atomic spectra measured with tangentially directed NPA in shots with different values of magnetic fields and plasma currents are shown. Strong drop of the NPA fluxes in the region of 15-28 keV at low values of currents and fields arises due to losses of fast ions during their slowing down. The drop weakens at current and field rise, so at $B_T = 0.8$ T and $I_p = 0.4$ MA it practically disappears, which indicates good confinement of fast particles. Thus, the ions with an energy of 50 keV, provided by the NB injectors, must be confined in Globus-M2 at B_T =1 T and I_p = 0.5 MA.

Lower Hybrid Current Drive

Globus-M2 is one of the few spherical tokamaks, which performs the LHCD experiment. As modelling predicts, an increase of the toroidal field improves the accessibility of the plasma center region. In experiment the antenna-grill was oriented so that the electric field of the wave in the waveguide was parallel to the equatorial plane of the tokamak and excited waves with poloidal deceleration $N_{pol} = 0$, while the main peak in the spatial $N_{||}$ spectrum had a value of $N_{||} \approx -3.0$. A typical decrease in the loop voltage when a RF pulse is applied is shown in Fig. 3. Depending on the value of the average density, the gap between the antenna and the separatrix, the input power, the effective plasma charge, the value of the relative voltage drop at the moment of application of the RF power varied within the range $\Delta U/U \approx (30 - 80)\%$, which corresponds to the value of the generated current $I_{LH} \approx (60 - 160)$ kA. The achieved efficiency $\eta = (0.15 - 0.4) \cdot 10^{19} \mathrm{Am^{-2}W^{-1}}$ is comparable with the values obtained on conventional tokamaks

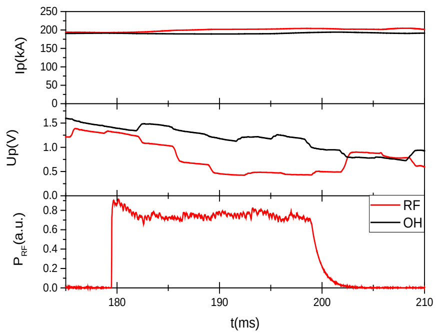

Fig.3 An example of the drop of loop voltage during of a RF pulse: #38686 (with RF) and #38694 (without RF). Discharge parameters: $B_T = 0.8$ T; $I_p = 200$ kA, $\langle n_e \rangle = 1.0 - 1.5 \cdot 10^{19} \mathrm{m^{-3}}$, $T_e(0) = 500$ eV, $Z_{eff} = 2.5$, $f_0 = 2.45$ GHz, $P_{inc} = 150$ kW, $N_{||} = -3.0$.

Alfvén Mode Investigation

The study of Alfvén modes (AM) was continued on Globus-M2. First of all, we were interested in the loss of fast particles caused by AM. The flux of charge-exchange atoms with energies close to the energy of injected particles (28 keV) was measured by means of NPA with the tangential line of sight. A drop in the flux at the time of the TAE burst indicated losses of fast ions. The regression fit of the Globus-M/-M2 data yields the following scaling for relative fast particle losses (NPA flux drop, $\Delta N/N$) on $(I_p \cdot B_T)$ and the relative TAE amplitude $(\delta B/B_T)$:

$$dN/N \sim \left(\frac{\delta B}{B_T}\right)^{0.37} \cdot (B_T I_P)^{-0.83} \quad ,$$

where δB is measured with an invessel Mirnov probe at the low field side. The level of losses grows with an increase in the TAE amplitude but decreases with increasing magnetic field and plasma current. The obtained dependence is promising for the operation of future compact fusion neutron sources (FNS) based on a spherical tokamak.

An increase in plasma parameters and better fast particle confinement led to a change in the nature of AM and the expansion of their frequency spectrum ($50 - 600$ kHz). Together with single toroidal Alfvén eigenmodes (TAE), observed earlier on Globus-M, multiple TAEs and so-called Alfvén cascades (AC) were identified. Observation of ACs made it possible to apply the method of MHD spectroscopy to determine the evolution of q_{min} in a discharge.

SOL Study

Globus-M2 has an open divertor which is equipped with Langmuir probes imbedded into divertor plates, movable 9-pin Langmuir probe in mid-plane and IR-camera. SOL width λ_q^{div} on the divertor target was obtained from heat flux profile. Then λ_q^{div} was mapped to the midplane with magnetic flux expansion index $\lambda_q^{mid} = \lambda_q^{div}/f_x$. The magnetic flux expansion was determined from magnetic equilibrium reconstruction with the help of current filament method. For typical lower single null discharges with $I_p = 200$ kA and $B_T = 0.7$ T λ_q^{div} is about 14-15 mm and f_x is $3.5 - 5$, so λ_q^{mid} is $3 - 4$ mm.

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References:

[1] V.B. Minaev, V.K. Gusev, Y.V. Sakharov, et al. // Nucl. Fusion **57** (2017) #066047.
[2] V.K. Gusev, V.E. Golant, E.Z. Gusakov, et al. // Tech. Phys. **44** (1999) 9, 1054-1057.
[3] G.S. Kurskiev, N.N. Bakharev, V.V. Bulanin, et al. // Nucl. Fusion **59** (2019) #066032.
[4] ITER Physics Basis Chapter 2: Plasma confinement and transport // Nuclear Fusion **39** (1999) 2175.
[5] N.N. Bakharev, F.V. Chernyshev, P.R. Goncharov, et al. // Nuclear Fusion **55** (2015) #043023.