NBI for Heating and Current Drive in Spherical Tokamak Globus-M, -M2

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Neutral Beam Injection (NBI) is the principal method for plasma heating and current drive in tokamak reactors since it offers the possibility of steady state operation. NBI is particularly important in compact fusion neutron sources based on spherical tokamak (ST) due to the limited number of auxiliary heating methods that can work under high density and relatively low magnetic field conditions. Therefore, one of the main operational goals for Globus-M and future Globus-M2 experiments is to investigate and demonstrate effective plasma heating and Neutral Beam Current Drive (NBCD).

The first section of the paper describes the latest experimental results on NBCD and NBI heating; the second presents the Globus-M2 NBI upgrade program, in particular injection geometry analysis and optimal experiment layout choice; finally, the third section discusses numeric simulations of main plasma parameters for Globus-M2 discharges with the injection of two neutral beams.

Experimental set-up

Globus-M ST [1] is equipped with a mid-plane NB injector designed for delivering 1 MW hydrogen/deuterium beam with the energy up to 30 keV [2]. Experiments were performed in plasma current range of 0.17 – 0.20 MA with toroidal magnetic field of 0.4 T. Experimental set-up is shown in Fig.1. The NBI impact parameter was 0.32 m. Hydrogen and deuterium were used as working gas both for target plasma and co-injected beam. Microwave interferometer was used for plasma density monitoring. Evolution of electron density and temperature profiles was recorded by means of Thomson scattering diagnostics. Ion component behavior was investigated with two neutral particle analyzers, one transversal and the other parallel to the beam line directions. Also the ion temperature was measured by means of CXRS.

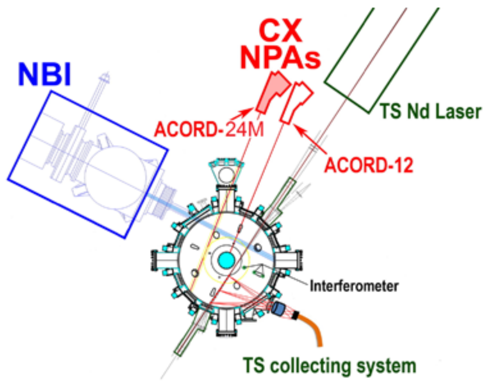

Fig. 1 Globus-M experimental set-up

Main experimental results on NBCD and NBI heating

In the last series of experiments, we investigated the dependence of a non-inductive fraction of the current on the isotopic composition of the beam and plasma [3]. Non-inductive current drive was recorded based on loop voltage drop at stabilized total plasma current. Hydrogen or deuterium beams (0.5 MW, 28 keV) were injected either into deuterium or hydrogen plasmas (170 kA) during the stationary phase of discharges. The values of non-inductive current calculated using the ASTRA code [4] are shown in Fig. 2. Bootstrap current is independent of isotopic combinations and definitely increases with density. The efficiency of NBCD is higher for hydrogen injection in comparison with the deuterium one, which can be explained by a significantly higher level of direct (shine through and first orbit) losses for the deuterium beam in Globus-M tokamak because of the relatively low toroidal magnetic field and small size of the machine.

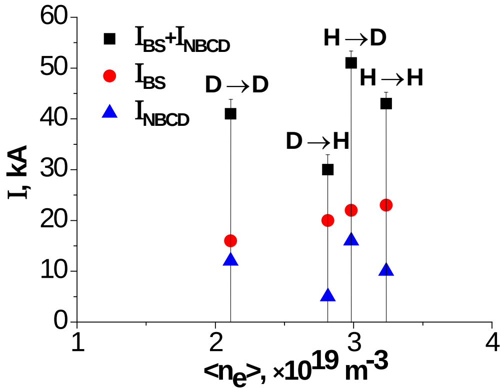

Fig. 2 Comparison of H- and D- NBI into hydrogen and deuterium plasmas, with I_{BS} – bootstrap current, I_{NBCD} – beam driven current

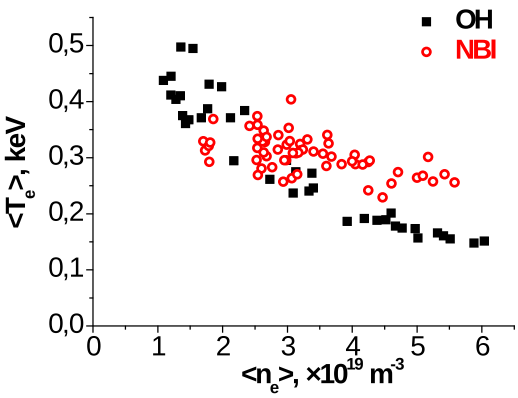

Fig. 3 Volume averaged electron temperature for NBI heated (red) and ohmic discharges (black) vs density

For the first time in Globus-M plasma discharges with NBI we obtained noticeable

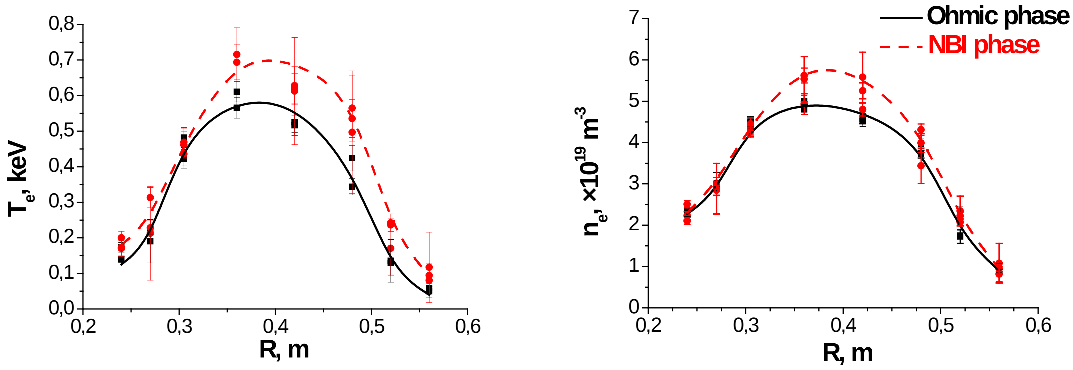

Fig. 4 Electron temperature and density spatial distribution in shot #35736 before and during NBI

electron heating (Fig. 3). For this study, we used deuterium plasma as a basic target and hydrogen beam with particle energy of 26-28 keV. Fig. 3 shows that electron heating is clearly observed for volume averaged density greater than 3.0×10^{19} m^{-3}, since shine through losses of fast particles reduce as density increases. Perceptible electron temperature rise is illustrated in Fig. 4, which shows electron temperature and density spatial distribution in shot #35736 (H plasma – 170 kA, D beam – 0.5 MW, 28 keV) before and during NBI. During NBI, electron temperature increases by 150 eV, particularly in central and outer plasma column region even in spite of density growth. It should be noted that generally electron heating starts in approximately 5 ms after the beginning of the injection and continues for about 10-15 ms followed by the degradation of discharge.

Globus-M2 NBI upgrade program

In Globus-M2, toroidal magnetic field and plasma current will be increased up to 1 T and 500 kA, respectively. In order to achieve effective heating by neutral beams, a corresponding increase of injected particle energy is required. Globus-M2 NBI upgrade program includes the modernization of the existing NB injector, commissioning of its new ion source, and installation of the second NB injector.

Power supply system modernization of the existing injector was performed, while the commissioning of new ion source designed for delivering 1 MW hydrogen/deuterium beam with the energy up to 40 keV and cross-section of about 18×6.6 cm has not been completed yet.

For the new injector, optimal experimental layout was chosen. A full 3D fast ion tracking algorithm [5] was applied to the calculation of fast particle losses for available values of the second injector impact parameter (27-32 cm). The results of this analysis are shown in Fig. 5, which represents the dependence of direct losses of fast particles on the available values of impact parameter. No significant difference in the values of direct losses at B_{tor} = 1 T and I_p = 0.5 MA was found, and the losses were minor (<5%); therefore, calculations were made at reduced B_{tor} = 0.7 T and I_p = 0.3 MA for two values of volume averaged density (5.0×10^{19} m^{-3}; 1.0×10^{20} m^{-3}) at 40 keV beam energy. On the basis of these simulations and due to design constraints, 30-cm impact parameter was chosen for the new NB injector.

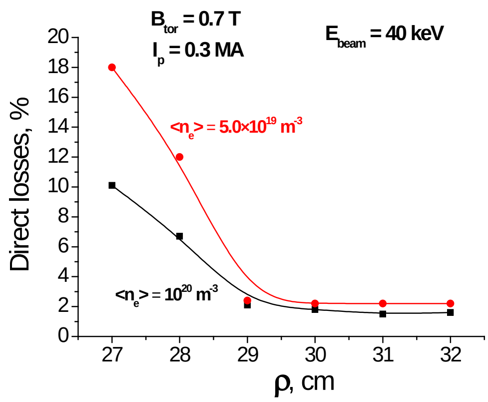

Fig. 5 Dependence of fast particle direct losses on possible values of impact parameter

Predicting plasma parameters for Globus-M2 discharges with the injection of two NB

Fast ion tracking algorithm was used for modeling fast particle losses, while numeric simulations of main plasma parameters for Globus-M2 discharges (I_p = 0.5 MA, B_{tor} = 1 T) were performed with the help of the ASTRA code. Input parameters for the calculation were the value of effective charge (Z_{eff} = 2), electron density profile (two cases of volume averaged density (a) 1.0×10^{20} m^{-3}; (b) 5.0×10^{19} m^{-3}), injection geometry, and neutral beam parameters. To calculate ion concentration, we assumed carbon as the main impurity. Heat balance equations for electron and ion components were solved in the model assuming neoclassical plasma heat conductivity (using NCLASS). Ion heat diffusivity was supposed to be equal to electron one but higher than neoclassical heat diffusivity and was determined so that the ratio of calculated energy confinement time to the time predicted by the ITER H-mode scaling τ_E^{IPB98} [6] be 1.3. It should be noted that typically confinement time τ_E^V in accordance with the Valovic scaling [7] is higher than the computed energy confinement time τ_E.

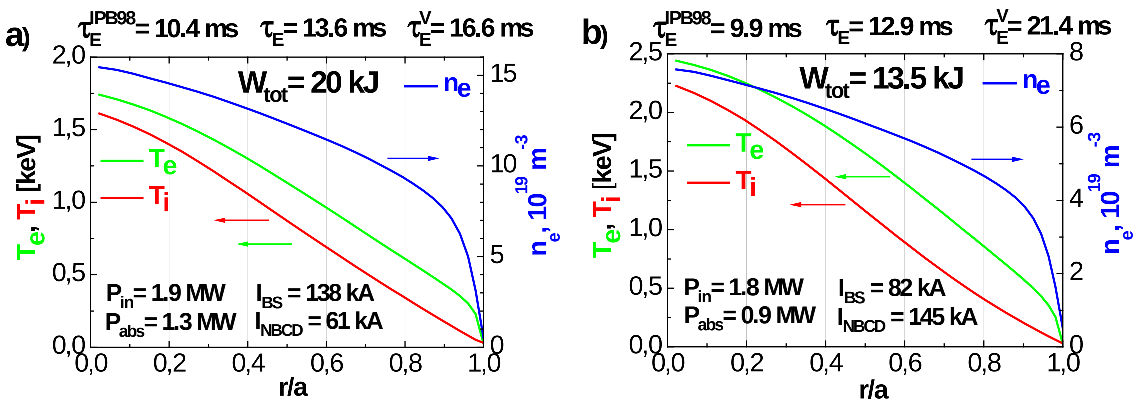

Fig. 6 Electron and ion temperature profiles for $\langle n_e \rangle = 1.0 \times 10^{20}$ m^{-3} (a), $\langle n_e \rangle = 5.0 \times 10^{19}$ m^{-3} (b); P_{in} – input power, P_{abs} – absorbed power, W_{tot} – total stored thermal energy

The results of these calculations are shown in Fig. 6. Numerical simulations indicate the achievement of conditions for better NBCD efficiency, higher fast particle confinement, and overall plasma performance. The total fraction of the non-inductive current is found to be about 40-45 %.

References:

[1] Gusev V.K., et al., Technical Physics, 44, 1054-1057
[2] Gusev V.K., et al., Technical Physics, 52, 1127-1143
[3] Shchegolev P.B., et al., Technical Physics, 60, 1321-1325
[4] Pereverzev G.V., et al., Report IPP 5/42, 1991
[5] Bakharev N.N., et al., Nuclear Fusion, 55 (2015), 043023
[6] ITER Physics Basis, Nuclear Fusion, 39 (1999), 217
[7] Valovic M., et al., Nuclear Fusion, 49 (2009), 075016

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