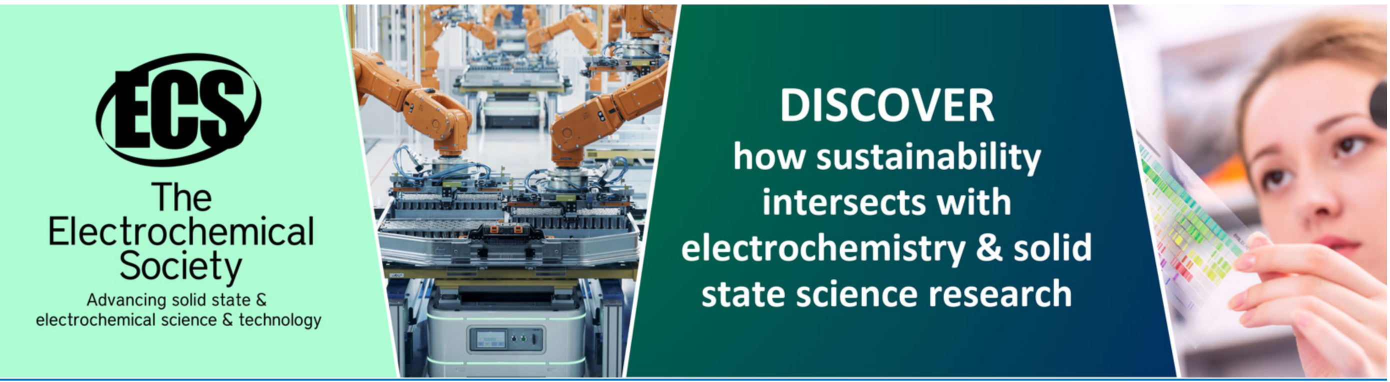
# Globus-M2 NBI upgrade and updated NBCD results obtained on spherical tokamak Globus-M





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# Globus-M2 NBI upgrade and updated NBCD results obtained on spherical tokamak Globus-M

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**Abstract.** The latest results are presented from NBCD experiments at the Globus-M spherical tokamak. The Globus-M2 NBI upgrade program is discussed, in particular, the analysis of the injection geometry and choice of the optimal experiment layout. The results from numerical simulations of plasma heating and current drive by two neutral beams in the Globus-M2 shots are also analysed.

## Introduction

The main problem of a tokamak-reactor which uses an inductor to create toroidal plasma current is its inherently cyclic pulsed operation. The reactor operation should be interrupted cyclically because the magnetization reversal is needed. To provide the continuous operation, the plasma current should be maintained by non-inductive methods. The development of appropriate techniques is a major step in designing a fusion neutron source based on tokamak. In fact, non-inductive current drive techniques are very important for spherical tokamaks where there is very little space for inductor winding. Neutral beam injection (NBI) is a popular and well reproducible technique for current drive in tokamak plasma. That is why one of the main goals of the Globus-M and the future Globus-M2 experiments is the study of the neutral beam current drive (NBCD).

## Experimental setup and main research techniques

Neutral beam injection system [1] of the Globus-M spherical tokamak [2] can deliver 1 MW of the additional heating power to the plasma by means of deuterium/hydrogen beam with the energy of up to 30 keV. Experiments were performed in tokamak plasma at two different toroidal magnetic fields of $B_{tor}$ = 0.4 and 0.5 T and a plasma current of $I_p$ = 0.17 MA. Beams were injected in the equatorial plane of the torus in the tangential direction along the plasma current, the impact parameter being 0.33 m. Hydrogen and deuterium were used as working gases for both the target plasma and injected beam. The electron temperature and density profiles were measured using the Thomson scattering diagnostics. The ion temperature and the losses of fast particles were calculated using data on the fluxes of atoms produced during charge exchange processes and measured by the neutral particle analyzers AKORD-12 and AKORD-24M. The charge exchange recombination spectroscopy [3] was used to measure the ion temperature.

**Main results on NBCD**

As of today, some progress in the NBCD studies was achieved at the Globus-M facility [4–6]. Non-inductive current drive was observed at the stabilized total plasma current, the value of NBCD being determined from the loop voltage drop. The deuterium beam (0.5 MW, 28 keV) was injected into the deuterium plasma (170 kA) during the stationary stage of the discharge (shot #34275). For the first time, in this shot the radial profiles of the current drive produced by the injection of high-energy atomic beam were calculated basing on the results of [7], the electron shielding current being taken into account (see [8]). The input parameters for the calculations were: the plasma effective charge ($Z_{eff}$ = 2.5), the electron density and temperature profiles, the injection geometry, neutral beam parameters and two different distributions of neutral atoms over the plasma column cross section assumed to be the top and bottom limits (see Figure 1a; ρ is the magnetic surface index). The magnetic configuration was calculated using data on the shapes of closed magnetic surfaces obtained by means of the EFIT code [9].

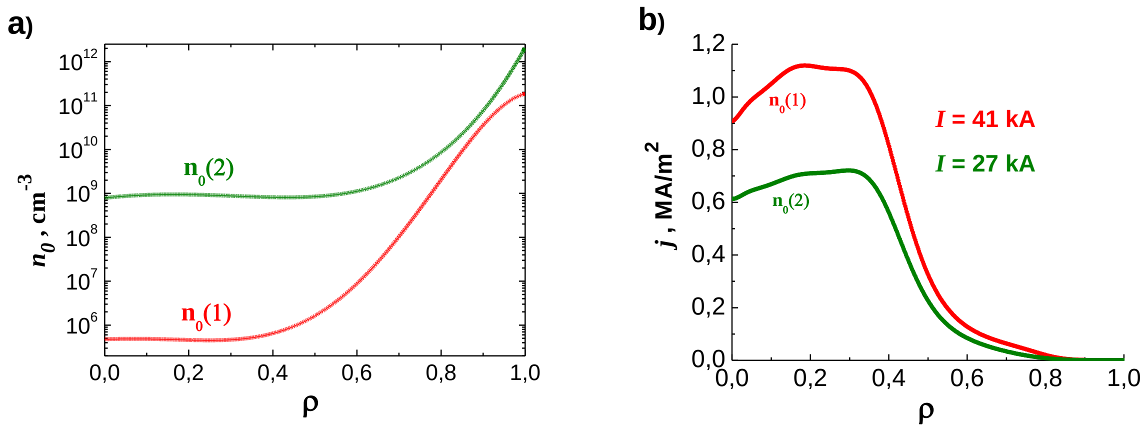


**Figure 1.** (a) Two different distributions of neutral atoms and (b) radial profiles of the current drive produced by the injection of high-energy atomic beam, the electron shielding current being taken into account.

At first, we calculated the source functions of particles on each magnetic surface for the three energy components of the injected beam taking into account the losses of fast particles. The total cross section of the electron losses for the beam atoms is composed of the cross sections for charge exchange processes of the beam atoms by plasma particles and cross sections for the ionization by the electron and ion impacts. Then, the kinetic equation is solved with allowance for the source functions obtained in the first step of calculations. Further, after calculating the deuteron distribution function, we calculated the fast ion current density profile. The calculation algorithm is described in detail in [7]. In the third step, the shielding effect of electrons is calculated according to [8]. As a result, we obtain the current density profiles for the fast ions produced by NBI for the two different profiles of neutrals' density (shown in Figure 1b) calculated with allowance for the electron shielding current.

In the last series of experiments with NBI on Globus-M, we studied the effect of the increase in the toroidal magnetic field on NBCD (the toroidal magnetic field $B_t$ was increased up to 0.5 T). In these experiments, the 0.95 MW hydrogen beams with particle energy of 28 keV were injected into deuterium plasmas ($I_p$ = 170 kA, $\langle n_e \rangle = 3 \times 10^{19}$ m$^{-3}$) during the stationary discharge stage at different toroidal magnetic fields. The poloidal magnetic flux consumption caused by NBCD is shown in figure 2. It is clear that the increase in the toroidal magnetic field by 20% (from 0.4 to 0.5 T) results in the lower consumption of the volt-second capacity of the inductor (up to 10%) which is caused by the additional toroidal current driven by the neutral beam. As the toroidal magnetic field grows, the losses of fast particles produced by high-energy atomic beam decrease, and fast ion confinement in plasma improves, resulting in the increase in the NBCD efficiency. Ultimately, we expect to achieve the significant progress in the NBCD studies at the Globus-M2 tokamak, in which the toroidal magnetic field is planned to be increased up to 1 T and a new high-energy neutral beam injector will be installed.

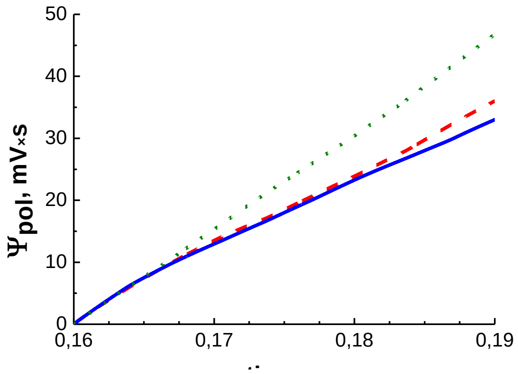


**Figure 2.** Poloidal magnetic flux consumption for NB heated #36932 (blue solid, $B_t$ = 0.5 T); #37017 (red dash, $B_t$ = 0.4 T) and ohmic #36902 (green dot, $B_t$ = 0.5 T) discharges.

**Modernization of the Globus-M NBI system**

The upgrade program for the Globus-M tokamak is aimed to increase the toroidal magnetic field and plasma current up to 1 T and 500 kA, respectively; therefore, the plasma density will also rise. To provide the efficient penetration of the fast beam atoms into the core of the plasma column, their energy has to be increased. The Globus-M NBI system upgrade program involves improvement of the installed neutral beam injector and installation of the additional neutral beam injector.

Currently, the production of a new ion source for the already installed injector which will be capable of generating the 1-MW-power neutral beam with energy of particles of up to 40 keV is nearly completed. To support its operations, a step-up autotransformer which allowed for the increase in accelerating electrode voltage to 40 kV was added into the high-voltage power supply circuit.

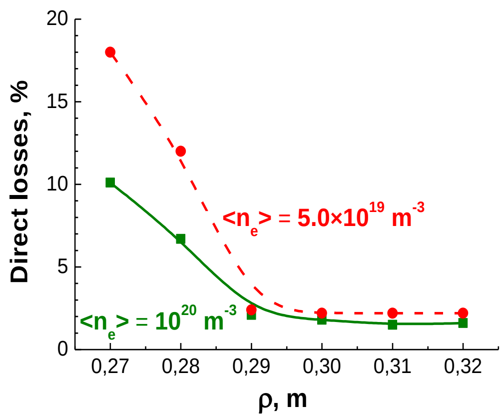


**Figure 3.** Direct losses of fast particles as a function of the accessible impact parameter ($B_{tor}$ = 0.7 T, $I_p$ = 0.3 MA, $E_{beam}$ = 40 keV).

The installation of the new injector required the analysis of injection geometry options, which served as the foundation for the experiment on the introduction of the second atomic beam in tokamak. Both atomic beams from two injectors were forwarded along the plasma current (co-injection) to accommodate design constraints. The optimal geometry of injection was chosen basing on the results of simulations of the direct losses of fast particles at the accessible impact parameters for the new injector (0.27–0.32 m) performed using the 3D algorithm [10] for tracing the particle trajectories. At the maximum toroidal magnetic field $B_{tor}$ = 1 T and current $I_p$ = 0.5 MA accessible in the Globus-M2 facility, the calculated losses were small (<5%) and were within the computational errors; therefore, calculations were performed at the lower magnetic field $B_{tor}$ = 0.7 T and current $I_p$ = 0.3 MA for two volume-averaged plasma densities ($5.0 \times 10^{19}$ m$^{-3}$ and $1.0 \times 10^{20}$ m$^{-3}$) at the beam energy of 40 keV. Figure 3 shows the calculated direct losses of fast particles as a function of the accessible impact parameter of the new injector. Basing on this analysis and taking into account the design constraints, the impact parameter of the second injector was set to be 0.30 m.

**Modeling of heating and current drive created by two neutral beams for Globus-M2 discharges**

The ASTRA code [11] was used to simulate the main plasma parameters for the Globus-M2 discharges ($I_p$ = 0.5 MA, $B_{tor}$ = 1 T) with the injection of two atomic beams (the first and the second beams have power of 0.9 MW and energy of 40 and 50 keV, respectively); whilst the modeling of fast particle losses was carried out using the fast ion tracking algorithm [10]. Input parameters for the calculation included the electron density profile (volume averaged plasma density $1.0 \times 10^{20}$ m$^{-3}$), plasma effective charge ($Z_{eff}$ = 2), parameters of two atomic beams and injection geometry. To calculate the ion density, we assumed carbon to be the main impurity. Energy confinement time $\tau_E$ was computed using the model, then compared with those predicted by the ITER H-mode scaling $\tau_E^{IPB98}$ [12] and the Valovic scaling $\tau_E^{ST}$ [13]. We note that the confinement time $\tau_E^{ST}$ generally exceeded the calculated $\tau_E$. In the model, the heat balance equations for electron and ion components were solved (using the NCLASS module) under the assumption that ion and electron thermal conductivities were equal, and they both exceeded the neoclassical thermal conductivity. The relation between the energy confinement times was defined to be $\tau_E = 1.3 \times \tau_E^{IPB98}$ (Fig. 4a).

The results of these calculations are shown in Figure 4b. Numerical simulations of the parameters of the Globus-M2 discharges with the injection of two neutral beams predict an increase in the ion and electron temperatures accompanied by the increase in the stored energy, energy confinement time and NBCD efficiency. In addition, calculations show that the total fraction of the current driven non-inductively will amount to approximately 40-45%.

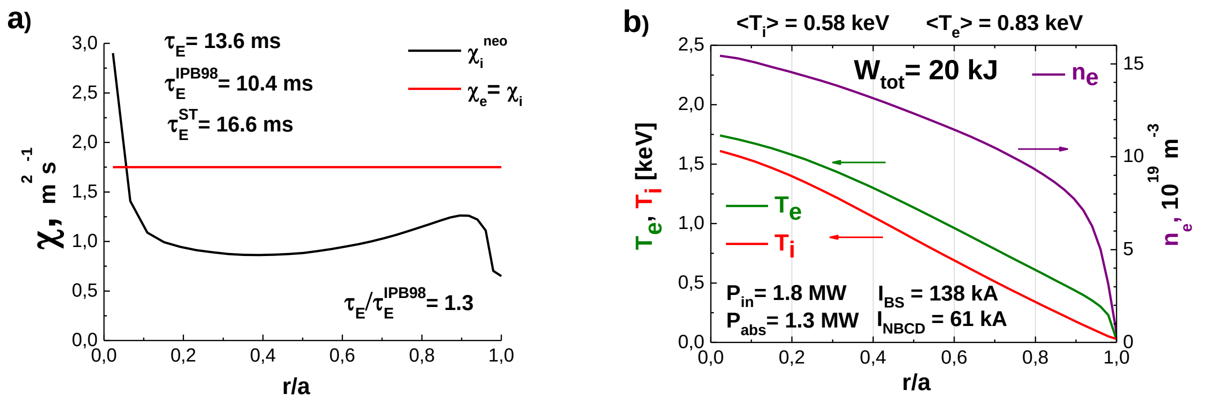


**Figure 4.** (a) Ion and electron heat diffusivities as compared to the neoclassical heat diffusivity calculated using the NCLASS module; (b) simulation results of current drive and heating by two neutral beams (50 keV and 40 keV); $P_{in}$ is input power, $P_{abs}$ is absorbed power, and $W_{tot}$ is total stored thermal energy.

**Conclusions**

For the first time, we calculated the current density profiles for the fast ions produced by the injection of high-energy atomic beam into the Globus-M plasma with allowance for the electron shielding current.

The effect of the increase in the toroidal magnetic field (from 0.4 to 0.5 T) on the NBCD was studied. With the toroidal magnetic field growing by 20%, the poloidal magnetic flux consumption decreased (by nearly 10%), which was caused by the NBCD efficiency growth.

The production of the new ion source of the installed injector capable of generating 1 MW NB with the energy up to 40 keV is nearly completed. For the new injector, optimal experimental layout was chosen, and its impact parameter was set to be 0.3 m.

Numerical simulations of the Globus-M2 discharges with the injection of two neutral beams predict an increase in the ion and electron temperatures accompanied by an increase in the stored energy, energy confinement time and NBCD efficiency. In addition, calculations show that the total fraction of the current driven non-inductively will amount to approximately 40–45%.

**Acknowledgments**
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