New 50-keV neutral beam injector for the Globus-M2 spherical tokamak

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Abstract. A design of the new neutral beam injector and the process of generation of a high-energy atomic beam are described in detail. The injector is fully prepared for experiments on auxiliary heating of the Globus-M2 tokamak plasma. The docking of injector with tokamak vacuum vessel is completed. The predictions for non-inductive current drive by 50 keV 1 MW neutral beam in the Globus-M2 are presented.

1. Introduction
One of the promising applications of spherical tokamaks is creation of the beam-plasma fusion neutron sources (FNS) [1]. Neutrons are the product of the fusion between beam ions and thermal tokamak plasma ions. The spherical tokamak Globus-M [2] operation has been finished [3], so the experiments will be continued on its upgraded version - spherical tokamak Globus-M2 [4-8]. After achievement of the design parameters (B_T up to 0.8-1 T and I_p up to 0.4-0.5 MA) Globus-M2 plasma characteristics will be closer to the future FNS ones [9-11]. In turn, it will be possible to significantly increase the plasma density. In this regard, to achieve the optimal beam penetration into the plasma before beam ionization, it is necessary to increase the energy of the injected particles.

Globus-M2 neutral beam injection (NBI) complex upgrade program [12-14] includes installation of the second NB injector in addition to the already existing one [15].

The main parameters of the new injector are as follows:
- Working gas: hydrogen, deuterium
- Particle energy range: 20-50 keV
- Ion current: 40A
- Output power: 1 MW
- Pulse duration: ≤ 1 s
- Fraction of full energy atoms: ~65%
- Beam divergence: 1.2°
- Focal distance: 3.5±0.5 m

As a result, the total NBI power will be doubled. Besides, the maximum pulse duration of the new injector exceeds the plasma discharge duration.

2. New NB injector design and the process of high-energy atomic beam generation
Scheme of the new NB injector with the designation of all the main elements is presented in Fig.1. The main functional units of the injector are: Ion source (1), Neutralizer (4), Bending magnet (7), Ion...
The injector can be easily undocked from the tokamak, thus allowing access inside the tokamak vacuum vessel. As a whole, the injector is placed on a trolley and adjusted to the tokamak. Thanks to this, the injector can be easily undocked from the tokamak, thus allowing access inside the tokamak vacuum vessel.

**Figure 1.** Scheme of the injector

1. Ion source
1.1. RF antenna
1.2. Pulse gas valve
1.3. Grids
2. Gate valves
3. Turbo molecular pump
4. Neutralizer
5. Vacuum tank
6. Cryopumps
7. Bending magnet
8. Ion dumps
9. Aiming device
10. Calorimeter
11. Trolleys

The principle of a high-energy atomic beam generation is based on electrostatic accelerating and focusing of the positive ion beam in an ion source with subsequent transformation into atomic beam due to charge-exchange recombination in neutralizer. The remaining ions are deflected by a magnet into the ion dump. The aiming device is used to adjust the position of the beam relative to the injection axis. The calorimeter provides measurements of total energy content and power profile for the generated atomic beam.

The injector ion source incorporates a RF plasma source and a multi-aperture electrostatic accelerator. In the accelerator, there is a set of three nested grids with the circular apertures to form an ion beam. The working gas is supplied to the gas discharge chamber through the plasma ignition unit. Plasma is produced by an inductively driven RF-discharge with a frequency of 4 MHz. High-frequency power is supplied to the antenna through an oil-insulated transformer.

The injector includes a set of subsystems providing its operation. The vacuum oil-free pumping system represents a turbomolecular pump with a foreline pump and two high-performance cryopumps, which are installed on top of the vacuum tank of the injector. The gas puff system consists of balloons, valves and pressure reducers and is intended for the dosed gas puff into the ion source. The water cooling system is specifically designed for cooling heat-stressed components of the injector (heat removal capacity ∼ 30 kW). The power supply system feeds all the devices and injector units. One part of it is located in the basement of the tokamak machine hall (high voltage supply of accelerating and locking electrodes of the ion source, bending magnet), the other one is placed in the vicinity of the injector (power supply of high-frequency discharge ion source). The control and data acquisition systems provide remote control of the technological processes and performs automated data recording for all injector subsystems.

A new neutral beam injector has been prepared for plasma experiments. The injector was installed in the experimental hall; connected to feeding and cooling systems; configured and tested (hydraulic and high voltage testing). The injector chamber was pumped to a pressure below $10^{-5}$ Pa. The injector was docked to the tokamak vessel with the help of the specially designed atomic duct (fig. 2).
3. Predictive simulations

To assess the effect of a high-energy atomic beam on plasma heating and the generation of non-inductive currents in Globus-M2 spherical tokamak, modeling was carried out using the ASTRA code [16]. Simulations were performed for deuterium and hydrogen beams during injection into a deuterium plasma with maximum parameters $I_p = 0.5$ MA, $B_T = 1$ T. Plasma density was varied in the range of $2.5\pm15\cdot10^{19}$ m$^{-3}$. The neutral beam with energy of 50 keV and power up to 1 MW started at the steady-state stage of a discharge.

The simulation was carried out under the following assumptions. For both the electron temperature and density, the direct transport problem solution was performed. The coefficient of electron thermal diffusivity was assumed to be constant over the profile and was calculated using the equation:

$$\chi = k\sigma_T/(4\cdot\tau_E^{d} P_{PB}(\nu, \nu'))$$ [17], [18].

The diffusion coefficient was defined as $D \approx \chi/2$. The particle pinching speed was assumed at the level of the Ware convection [19]. The coefficient of ion thermal diffusivity was chosen as neoclassical, since spherical tokamaks [20], including the tokamak Globus-M [21], are characterized by the neoclassical ion heat transport. Carbon was assumed as the main impurity. The effective plasma charge $Z_{eff}$ was supposed to be constant throughout the plasma column and was about 2.5. Absorbed beam power was calculated by standard subroutine of the ASTRA code. Additional corrections were made for absorbed power in order to take into account first orbits losses of fast particles. These losses were determined using a three-dimensional modeling algorithm [22]. The results of these calculations are shown in fig. 3. As can be seen from the figure, the high non-inductive currents fraction was reached. The maximum total non-induction current ($I_{SUM}$) can be achieved in the mode with average plasma density about $<n_e> = 5\cdot10^{19}$ m$^{-3}$ for deuterium beam and $<n_e> = 6\cdot7\cdot10^{19}$ m$^{-3}$ for hydrogen beam. Bootstrap current ($I_{BS}$) was the main fraction for the high level of the plasma density while neutral beam current drive ($I_{CD}$) was at the significant level for the low and moderate density. But there wasn’t found the substantial difference between beam isotopes and total non-induction fraction was about 25%. The effective generation of non-induction currents is a consequence of the improving confinement of fast beam particles due to plasma current and toroidal magnetic field increasing.

**Figure 2.** Docking of the injector with the Globus-M2 tokamak vessel
4. Summary

On the spherical tokamak Globus-M2, the preparation of the NBI complex was completed for auxiliary plasma heating experiments. First of all, preparation included commissioning works for a new NB injector. As a result, the new injector was installed in experimental hall and docked to the tokamak. The connection and testing of its main systems were carried out. The existing NB injector was also prepared for the experiment with the ISPM-1 (peripheral magnetic field) ion source [15]. Thus, the neutral beam injection complex is able to generate two beams of hydrogen or deuterium atoms with particle energy up to 30 keV and 50 keV, with a total output power up to 2 MW. The power level of auxiliary heating provided by the two injectors exceeds the ohmic power several times.

Numerical simulations predict improved fast particle confinement and overall plasma performance in the Globus-M2 spherical tokamak. Better conditions for a non-inductive current drive are also predicted. The total fraction of non-inductive current is found to be about 25% for the 1 MW level of NBI. This is a promising result for upcoming plasma experiments.

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