The Globus-M2 spherical tokamak: the first results

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Abstract. The Globus-M2 spherical tokamak is the considerably upgraded Globus-M facility. Its technical parameters were increased as much as possible to achieve the promising range of physical parameters (sub-fusion temperatures and collisionality of much less than unity). These parameters will be achieved in a compact magnetic configuration similar to that of the Globus-M tokamak, the plasma current and toroidal magnetic field amounting to 0.5 MA and 1 T, respectively. The demand to increase the magnetic field and plasma current in the Globus-M2 resulted in the need for a complete redesign of the electromagnetic system because the plasma equilibrium requirements have changed and the mechanical and thermal loads have considerably increased as compared to the Globus-M. The vacuum vessel and the in-vessel components of the new Globus-M2 tokamak remain the same. Power supplies were upgraded to provide the required currents in the toroidal field coil and the central solenoid. The Globus-M2 tokamak was build up and preliminary tests were carried out. New auxiliary heating systems and diagnostics were developed and installed to be used in future experiments. First plasma was achieved at the Globus-M2 in April 2018.

1. Introduction
The main factor that hampered the improvement of plasma parameters in the Globus-M spherical tokamak [1] was a relatively low toroidal magnetic field [2–5]. An increase in the magnetic field (from 0.4 T up to 1.0 T) and plasma current (up to 0.5 MA) in the upgraded tokamak [6, 7] should promote plasma performance and provide improved conditions for auxiliary heating and current drive [8].
A shot with high electron density ($<n_e> = 0.7 \times 10^{20} \text{ m}^{-3}$) and deuterium beam injection (1 MW) was chosen to estimate the plasma parameters with increasing toroidal magnetic field. The ASTRA and NUBEAM codes were used for simulations. We believe that the particle transport remains the same as in the Globus-M plasmas. To describe the ion thermal conductivity, an additional anomalous term was added to the neo-classical one. The electron thermal conductivity was estimated with the help of two scalings. The ITER IPB98(y, 2) scaling [9] was taken as a pessimistic one. The so-called ST-scaling [10] was considered as an optimistic prediction. Nevertheless, in both cases, the electron temperature in the plasma core exceeds 1.5 keV.

In terms of the auxiliary heating and non-inductive current drive applications [11–14], it is favorable to increase the toroidal magnetic field. Under new conditions, the ions with energies up to 100 keV are well confined in plasmas. During IC heating, the absorption of input power increases due to the improved antenna-plasma coupling. The NB heating becomes more effective too: the percentage of direct power loss drops considerably, even in the case of injection of particles with higher energies. This fact is very important for the NBCD experiments. Approximately half of plasma current is a non-inductive current excited as a result of simultaneous injection of two 1 MW neutral beams. Low-hybrid wave (2.45 GHz) application provides fully non-inductive current drive for inputted power of approximately 0.5 MW. During the deuterium beam injection into deuterium plasmas, we also expect an increase in neutron flux by at least two orders of magnitude as compared to the Globus-M.

2. Design of the Globus-M2 tokamak
Two basic plasma shot scenarios were considered when designing the upgraded Globus-M2 facility (see Table 1). The first one ("B-max") assumes the tokamak operation with the maximal toroidal magnetic field of 1 T and plasma current of 0.5 MA, which is mostly driven by the central solenoid. The second scenario ("t-max") was considered for experiments with non-inductive current drive. In this case, the toroidal magnetic field will be reduced to 0.7 T, but the field flat top will be made as long as possible.

| Engineering parameter | B-max regime | t-max regime |
|------------------------|--------------|--------------|
| Plasma current | 0.5 MA | 0.5 MA |
| Central solenoid flux consumption | 0.4 Wb (+/- 0.2 Wb) | 0.4 Wb (+/- 0.2 Wb) |
| Duration of TF flat top | ≤ 0.4 s | ≤ 0.7 s |
| Basic regime | Inductive / Noninductive | Noninductive CD |
| TF field ripple at R = 0.6m | ≤ 0.4% | ≤ 0.4% |
| Maximum number of working pulses in regime | 5000 | 10000 |
| Minimal pulse repetition rate | Every 15 min | Every 15 min |

For the upgraded tokamak, the design of magnets was completely revised [8]. High-grade materials were used in the electromagnetic system manufacturing. Inner segments of the toroidal magnetic field coils and central solenoid were made from durable cold extruded copper alloy. All coils are water-cooled. The electromagnetic system support structure was considerably enhanced too. The additional upper supporting ring, which is jointed to the bottom one by four load-bearing crosspieces, limits the amplitude of the toroidal field coil displacement to less than 3 mm. In addition, the toroidal field ripples at the plasma outer boundary were reduced down to 0.4%. In accordance with the B-max scenario, the electric current through the toroidal field coil will amount to 110 kA providing the magnetic field of 1.0 T. Current swing in the central solenoid is ±70 kA. The tokamak vacuum vessel
and the in-vessel components remained the same because they meet new conditions; that reduces the project costs.

3. The Globus-M2 experimental setup

New systems for auxiliary heating and non-inductive current drive will be installed at the Globus-M2 tokamak. For the existing NB injector, the maximal energy of atoms is increased up to 40 keV. The beam pulse duration is also increased. A new injector, which provides the 50 keV atomic beam with 1 MW power, will be applied in addition to the first one. Both beams are co-injected tangentially to the plasma column. A new waveguide line provides transmission of about 0.5 MW of RF-power from the 2.45 GHz klystron generator to the LHCD grill antenna. A new version of the grill was manufactured and tested. A new double-strip antenna for IC heating system was manufactured too. Installation of the new equipment led to some rearrangement of the diagnostic setup. The layout of the auxiliary heating systems and the main diagnostics is shown in Figure 1.

4. Preparations for the first plasma experiments

The Globus-M2 spherical tokamak has been fully assembled and installed in the machine hall (see Figure 2). The tokamak AC and DC power supplies were simultaneously upgraded. Some of them were successfully tested during the final Globus-M experimental campaign. The legacy NBI system is ready for operation. Its water cooling subsystem was upgraded together with the tokamak cooling subsystem. The new NBI system, which provides the quasi-continuous operation, is under assembling and will be ready by the end of the year. Upgrade of 2.45 GHz LHCD system is on the way, including a new 1-s-duration power supply for the klystron generator, novel antenna with the 10-waveguide grill and waveguide divider of RF power. Some new diagnostic systems have been tested previously at the Globus-M facility.
The electromagnetic system of the tokamak was connected to regular power supplies. The magnetic diagnostics, consisting of a set of loops and probes, was connected to a data acquisition system and used during complex tests of the electromagnetic system. Test currents were passed through the separate groups of the poloidal field coils and the generated magnetic fluxes were recorded. The results of measurements for some of the coils are shown in Figure 3. The symmetry of the magnetic flux distribution relative to the middle plane of the tokamak indicates a good quality of manufacturing and assembling of the electromagnetic system of the Globus-M2 tokamak.

Figure 2. The Globus-M2 tokamak in the machine hall in the final stage of assembling.

Figure 3. Reconstructed lines of the constant poloidal flux exited by the central solenoid (left) and by a pair of PF1 coils (right).

5. Summary
To date, the assembling of the new Globus-M2 spherical tokamak was completed. A new electromagnetic system was tested, and no discrepancies with the designed parameters were revealed. In April, the first plasma was obtained in the working shots with a current of 0.15 MA and the toroidal magnetic field of 0.5 T. A full-scale plasma experiment will begin by the end of the year.

Acknowledgments
The work is performed at the Unique Scientific Facility "Spherical tokamak Globus-M", which is incorporated in the Federal Joint Research Centre "Material science and characterization in advanced technologies”. The work was supported by the Ministry of Education and Science of the Russian Federation (id RFMEFI62117X0018) and the Federal Agency for Scientific Organizations.

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