Status of the spherical tokamak Globus-M2 project

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The Globus-M spherical tokamak [1] has demonstrated practically all of the project objectives since it started operating in 1999. The main factor limiting further enhancement of plasma parameters is a relatively low toroidal magnetic field [2]. The increasing of the magnetic field (from 0.4 T up to 1.0 T) together with the plasma current (up to 0.5 MA) in the upgraded tokamak should promote plasma performance and provide improved conditions for auxiliary heating and current drive [3,4].

Conception of the tokamak upgrade

In the upgraded device the vacuum vessel, in-vessel components and diagnostics remain the same that allows reducing project costs. Design of the magnetic system and supporting structure is substantially revised [5]. Simulations of mechanical and thermal loads were performed for two plasma shot scenarios. The first one (so-called "B-max") assumes tokamak operation with maximal toroidal magnetic field of 1 T and plasma current of 0.5 MA. The second scenario (so-called "t-max") was considered for experiments with non-inductive current drive. For this case the toroidal magnetic field is reduced to 0.7 T, but the field flattop is as long as possible. The comparison of the "B-max" Globus-M2 OH scenario with the Globus-M one is presented in figure 1. The electric current through the toroidal field (TF) coil reaches the value of 110 kA providing the magnetic field of 1.0 T. The plasma current is mostly driven by the central solenoid (CS). The magnetic flux consumption

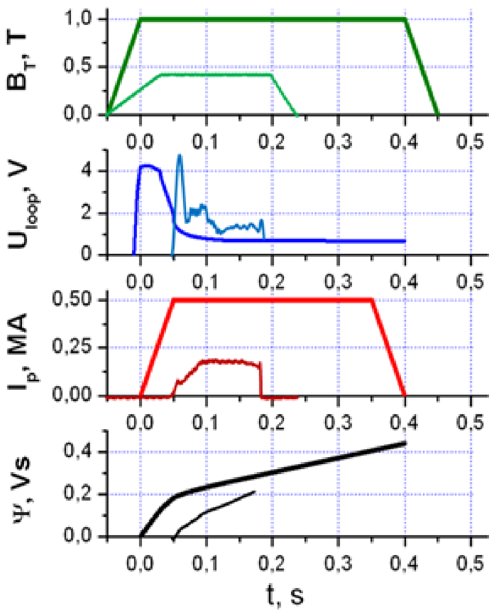

Figure 1. Comparison of a simulated Globus-M2 "B-max" OH scenario (thick lines) with the Globus-M scenario (thin lines)

$\Psi \sim 0.4$ V×s corresponds to the solenoid current swing of ± 70 kA. This requires power supply upgrade in order to increase the output voltage. The plasma current ramp-up rate is 10 MA/s for both scenarios.

In the present device the TF ripple near plasma boundary is sufficiently high (0.6–0.8%). In order to reduce ripple (approximately by a factor of 2) the radius of TF coil outer limbs will be increased from 800 mm to 840 mm. The contours of the present and new TF coil together with the field ripple variation along the major radius in the equatorial plane are shown in figure 2. The TF coil is self-supported and serves as supports for poloidal field (PF) coils. The increase of the TF coil overall diameter requires manufacture of two pairs of outer PF coils. Nevertheless, their coordinates stay practically unchanged, which allow keeping the full set of plasma magnetic configurations available in Globus-M.

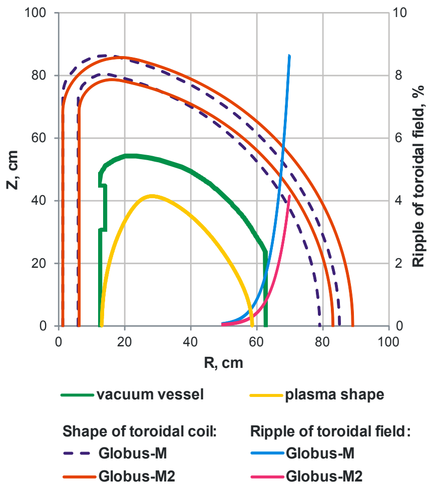

Figure 2. TF ripple comparison in the Globus-M (dashed) and Globus-M2 (solid) design

Design description

A 3D view of upgraded magnetic system enhanced with new support rings and crosspieces is shown in figure 3. Performed thermal analysis revealed possible overheating of the TF coil inner segments. Therefore, the conducting area of TF coil inner segments is increased, whereas the new solenoid conductor cross-section is decreased (20×15 mm^2 instead of present 20×20 mm^2). Simultaneously, the gap of 10 mm between the central column and the vessel inner cylinder in Globus-M allows an increase of the total column diameter in Globus-M2 reducing the gap value to approximately 3 mm. Rated pause for water cooling between shots is 15 minutes. Hollow conductors for the TF coil inner segments are manufactured from silver bearing cold extruded copper (yield strength $\sigma_{02} > 240$ MPa). 16 inner segments of TF coil are insulated with prepreg and

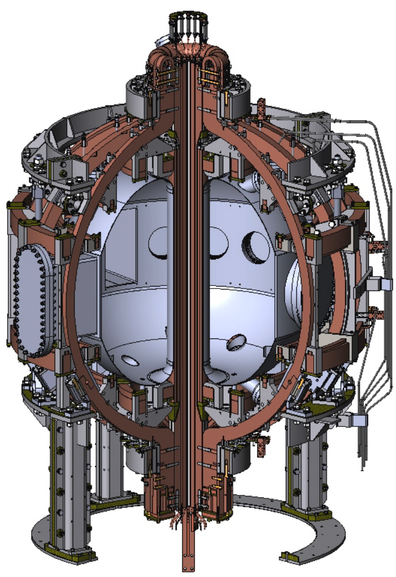
Figure 3. Magnetic system of the Globus-M2 tokamak

assembled as single rod. In order to withstand shear stresses in insulation the rod is enhanced with insulated dowels inserted between segments. The outer limbs are made of high grade silver bearing copper (σ_{02} > 220 MPa). New electric contacts of TF coil are unloaded mechanically. The inner segments and the outer limbs of TF coil are connected with flexible bus bars. Upper contact area is significantly enlarged in comparison with Globus-M. Upper and lower contact zones are reinforced with bandage rings.

The temper hard copper conductor (σ_{02} > 290 MPa) of trapezoidal cross-section (20.6-19.4×15 mm) with cooling channel at the center was chosen as material for the CS. The conductor is wound in two layers in situ around the TF coil inner rod. It is planned to manufacture full scale solenoid prototype in order to elaborate technology of winding providing thin gap between the solenoid and the TF rod. All PF coils are also manufactured from hollow conductors and water cooled.

Supporting structure for the magnetic system was reinforced substantially. New upper supporting ring is bonded with lower one by means of four load-bearing crosspieces, which prevent the displacement of the TF coils in toroidal direction. The intercoil bracing is also strengthened. Stainless steel is used as material for supporting structure.

The complete 3D finite element model (see figure 4) was developed and applied for mechanical and thermal stress analysis. This model includes poloidal and toroidal field coils as well as main components of supporting structure such as intercoil bracing, bearers, supporting rings, bandage rings and load-bearing crosspieces. The contact interfaces between elements of the tokamak magnet and supporting structure were modeled using special contact elements. Submodelling technique was used for detailed stress analysis of the supports. The highest possible operation loads corresponding to the "B-max" regime were taken into consideration. As it's seen from calculations, maximal out of plane loads on the TF coil occur during disruption at the end of toroidal field plateau. Nevertheless, maximal displacement of the

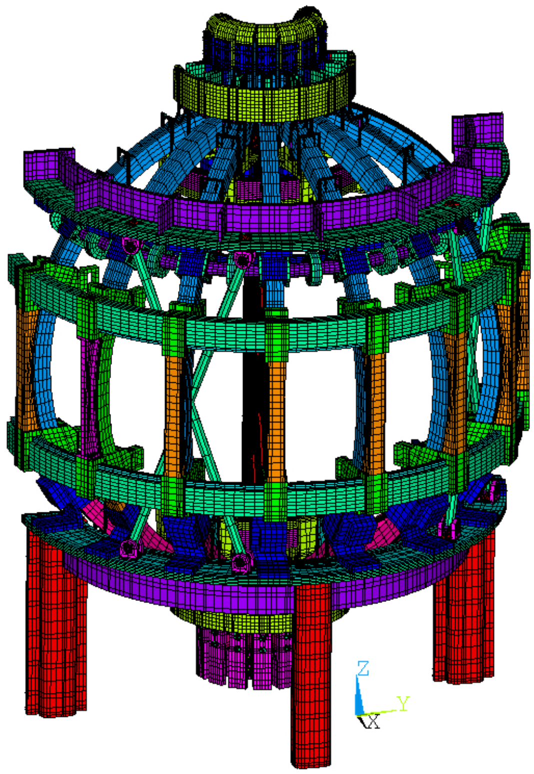

Figure 4. 3D finite element model of coils and supporting structure

TF coil in toroidal direction does not exceed 3.2 mm (see figure 5). This relatively small value is achieved due to the special load-bearing crosspieces, which undergo a pulling force of 43.5 kN and compressing one up to 26.5 kN (safety margin for buckling for the unit is equal to 4.25). Calculations show that stresses in the coils and supporting structure are within the allowable limits, and lower intercoil bracing which exists in Globus-M, is not more required. As results from the actual design, the operating limit of the upgraded tokamak is estimated as 30000 shots, including at least 5000 shots with maximal values of the toroidal magnetic field and plasma current.

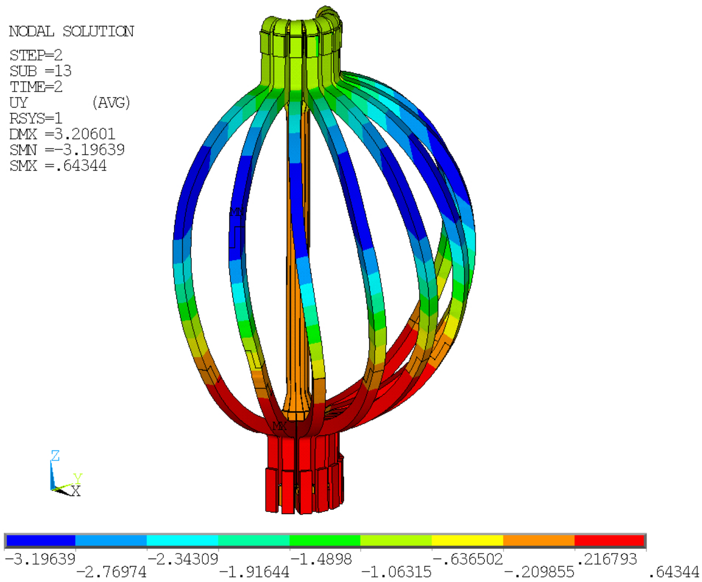

Figure 5. Displacement of the TF coil in toroidal direction, mm

Current status of the tokamak upgrade

The detailed design of the tokamak upgrade was mostly completed in 2013. Prototypes of the insulated dowel joints of TF inner rod were manufactured and tested. Half-finished material for TF rod has been manufactured at KME Germany GmbH & Co. KG and delivered to the Ioffe Institute. Workpieces for the TF coil outer limbs and conductors for the PF coils and central solenoid have been manufactured by Luvata Pori Oy, Finland and also shipped to Saint Petersburg. The manufacturing of a new magnetic system was started in the beginning of 2014.

This report employs the results, which have been obtained with the help of the unique scientific device spherical tokamak Globus-M.

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