

## Globus-M modernization and plasma parameter promotion in the basic plasma heating and CD scenarios

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The necessity of toroidal magnetic field increase is evident from experiments conducted in the spherical tokamak Globus-M and numerical simulations, especially in the shots with powerful auxiliary heating [1-3]. Modernization of the tokamak (project Globus-M2), which is planned in the near future, means toroidal magnetic field (TF) increase from the present value of 0.4 T up to 1 T as well as the plasma current rise up to 0.5 MA. Reconstruction of the magnetic system will basely deal with the new central stack design, leaving the poloidal field coil system without serious rearrangement and the vacuum vessel unchanged. In the current report benefits of TF increase for the basic Globus-M scenarios of plasma heating, CD and gain in physical parameters are reviewed, avoiding discussion of technical issues connected with the TF increase.

Plasma shot with the toroidal magnetic field value of 1 T and the plasma current of 0.5 MA was chosen as a basic scenario. The current increase rate was set as 10 MA/s. Evolution of plasma current, currents in the toroidal field coil and in the central solenoid, as well as the loop voltage are shown in figure 1. The neutral beam of 1 MW power is switching on at 25 ms after the plasma current attains plateau. The existing design of the magnetic system [4] is taken as a basis. But the central rod gains 10 mm in diameter due to reduction of gap between the central solenoid and the vacuum vessel. Cold extruded silver bearing copper is chosen as the material for the inner segments of the TF coil for better electroconductivity and mechanical properties. Under

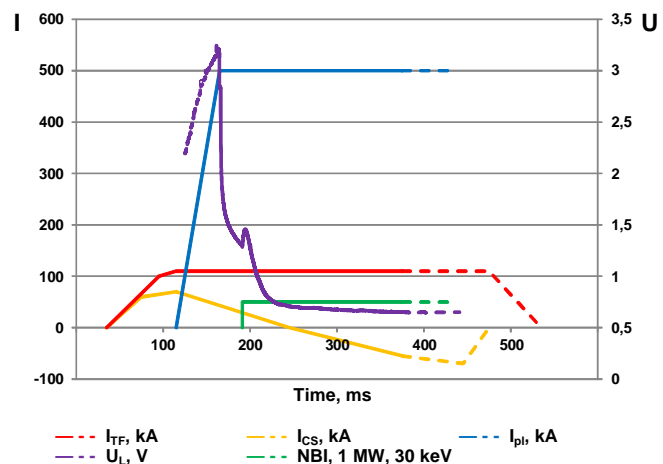


Figure 1. Basic scenario of shot with toroidal field value of 1 T for Globus-M2 tokamak.

these conditions the plasma current plateau is limited to  $\sim 200$  ms by allowable temperature of the central rod for the regime with maximal toroidal field. Vice versa in the alternative scenario with the magnetic field reduced to 0.7 T the plasma shot duration is limited by volt-second capacity of the poloidal magnetic system. Nevertheless it has about the same value without application of non-inductive CD methods.

Simulation of expected Globus-M2 plasma parameters was performed with the help of the ASTRA numerical code [5] for the deuterium plasma and the hydrogen neutral beam. Calculations started from the plasma current value of 50 kA. Plasma conductivity and ion temperature diffusivity were calculated with the help of the NCLASS code. Electron temperature diffusivity was taken in accordance with the ITER scaling for L-mode and IPB98 (y,2) for H-mode which agreed well with Globus-M existing database. Although ion thermal diffusivity in Globus-M is neoclassical, in our simulations we used superposition of neoclassical temperature diffusivity and anomalous one. The last one was set to be equal to particle anomalous diffusivity. Experimentally measured density and temperature profiles for the magnetic field of 0.4 T were taken as initial conditions. Density rise rate was taken from experimental database too. At the end of current ramp-up the averaged density reached  $5 \times 10^{19} \text{ m}^{-3}$  and H-mode was switched on. Parameters for existent neutral beam with 1 MW total power and 30 keV particles energy were applied. Calculations of absorbed beam power and non-inductive current were performed with the help of the NUBEAM subroutine [6]. Figure 2 demonstrates evolution of main plasma parameters. Saw-teeth aroused shortly after start of the beam. In our simulation we used Kadomtsev reconnection model [7,8] for this oscillations. Nevertheless, the central electron and ion temperatures reach values of 1.3 and 1.8 keV correspondently for the density of  $9 \times 10^{19} \text{ m}^{-3}$  in

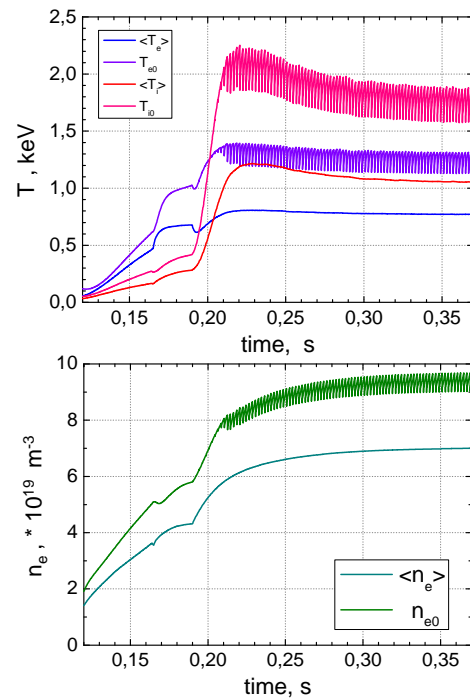


Figure 2. ASTRA code simulation of main plasma parameters for the Globus-M2 basic scenario.

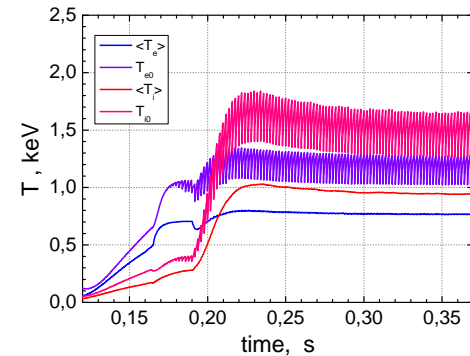


Figure 3. Evolution of temperature in the shot with magnetic field reduced down to 0.7 T.

the core. About a quarter of the plasma current had non-inductive nature. Note that toroidal field reduction down to 0.7 T does not influence significantly on the electron temperature (see fig. 3). Also it is very important that the plasma current plateau duration is by a few times longer than the energy confinement time, which is about 10-12 ms in our calculations.

Also we analyzed ICR heating at a fundamental harmonic of hydrogen minority in deuterium plasma. Due to increase of the toroidal magnetic field by factor of 2.5 the resonance frequency rises from 7.5 MHz to approximately 18 MHz. Distinguishing feature of the Globus-M experiment was a wide range of hydrogen concentration in deuterium plasmas  $n_H/(n_H+n_D) \approx 10\text{-}70\%$ . Numerical simulation of FMS wave propagation and absorption in Globus-M2 [9] was performed for the concentration of hydrogen in the range of 10-40% at

15 MHz ion cyclotron resonance frequency located near plasma column axis. As it is seen from calculations, RF power absorption is at least twice as high in the upgraded tokamak. Comparison of power absorption by different plasma components in present and designed device for 10% of hydrogen is shown in table 1. Total absorbed power in Globus-M is chosen as unity. Figure 4 demonstrates the spatial distribution of absorbed power by different plasma components for the same concentration of light minority.

Non-inductive plasma CD simulation was made for the low hybrid frequency range. Ten-waveguide grill, which is at present under construction, was taken for calculations. Operating frequency of

2.45 GHz is higher than lower hybrid one for given conditions ( $\langle n_e \rangle = 2 \times 10^{19} \text{ m}^{-3}$ ,  $B_T = 1 \text{ T}$ ,  $I_p = 0.5 \text{ MA}$ ,  $T_e = 1 \text{ keV}$ ). The FRTC low hybrid ray-tracing code [10] was applied. The details are presented in [11]. High efficiency of non-inductive CD was shown, that is very important. Figure 5 demonstrates the distribution of current density for two different orientations of grill on the LFS of the torus: conventional position along toroidal direction and

Table 1. Comparison of power absorption by different plasma components in Globus-M and Globus-M2 tokamak.

| Specie | $P_{\text{abs}}$ at 0.4 T<br>(arb. un.) | $P_{\text{abs}}$ at 1.0 T<br>(arb. un.) |
|--------|---|---|
| $e^-$  | 0,641                                   | 1,001                                   |
| $p^+$  | 0,260                                   | 0,824                                   |
| $d^+$  | 0,099                                   | 0,344                                   |
| Total  | 1,000                                   | 2,169                                   |

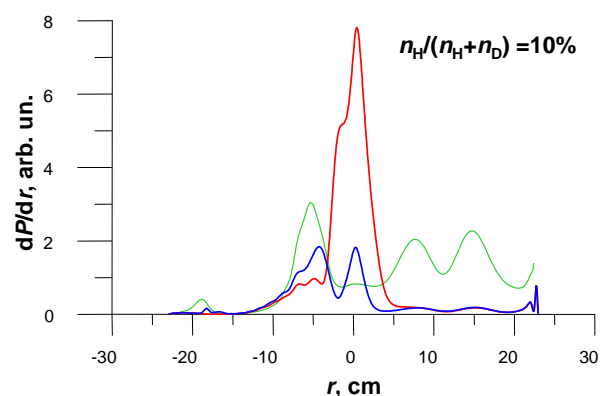


Figure 4. Spatial distribution of ICH power, absorbed by plasma components: red - protons, blue - deuterons, green - electrons.

alternative one directed poloidally. It's clearly seen that the first case is preferable due to higher driven current. Its integrated value over the cross-section is about 460 kA and is close to the total plasma current for the input power of 0.5 MW.

As we believed, the toroidal magnetic field increase up to 1 T allows using of the UHF wave range for plasma heating in Globus-M2.

Preliminary calculations showed that the bulk of plasma cross-section is accessible (no cutoff) for the second harmonic of electron cyclotron resonance (55-60 GHz for  $n_e \sim 3 \times 10^{19} \text{ m}^{-3}$ ). However due to strong radial gradient of magnetic field the optical thickness of resonance zone is narrow. For the reasons given above the single-pass absorption is weak, and the usual O-mode scheme of electron cyclotron heating is not effective. More complicated heating scenario [12] can be used in principle, but scrupulous analysis is required.

Summarizing said above, we ascertained that the increasing of the toroidal magnetic field together with the plasma current promotes plasma performance and provides improved conditions for auxiliary heating and current drive in Globus-M2.

The work is supported by Russian Academy of Science, Ministry of Education and Science of Russia as well as by the RFBR grants ## 10-02-01421, 10-02-00746, 11-02-00381.

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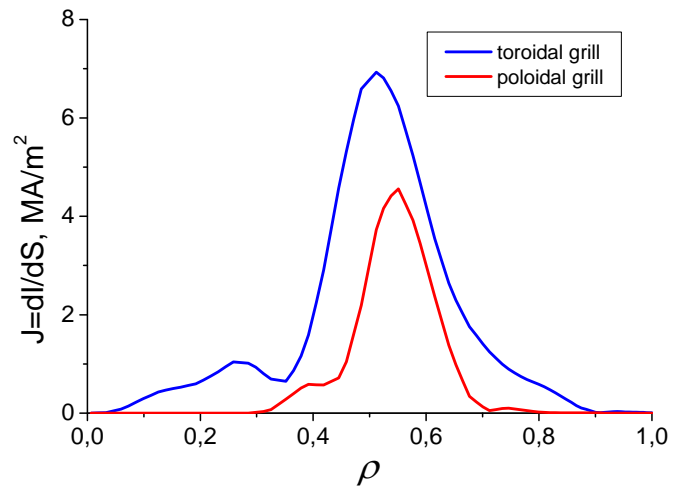


Figure 5. Distribution along minor radius of Globus-M2 tokamak of non-inductive current driven by LH-waves for two different orientations of grill.