Modeling of the fast ion behavior in the Globus-M spherical tokamak

N.N. Bakharev[1)], F.V. Chernyshev[1)], P. R. Goncharov[2)], V.K. Gusev[1)], A.D. Iblyaminova[1)], V.A. Kornev[1)], G.S. Kurskiev[1)], A.D. Melnik[1)], V.B. Minaev[1)], M.I. Mironov[1)], M.I. Patrov[1)], Yu.V. Petrov[1)], N.V. Sakharov[1)], P.B. Shchegolev[1)], S.Yu. Tolstyakov[1)], G.V. Zadvitskiy[2,3)]

[1)] *Ioffe Institute, St. Petersburg, Russia*
[2)] *Peter the Great Polytechnic University, St. Petersburg, Russia*

[3)] *IJL UMR 7198 CNRS - Université de Lorraine, BP 70239, F-54506 Vandoeuvre-lès-Nancy, Cedex France*

Introduction

Fast ions will play a key role in the future compact fusion neutron sources (CFNS) and two-energy component fission-fusion hybrid reactors based on the concept of a spherical tokamak [1]. Understanding of their behavior is essential for the design of future machines and choice of their operation modes. However it is not studied in details in contrast to the fast ion behavior in conventional tokamaks due to the difficulties in interpretation and a low number of spherical tokamaks with significant auxiliary heating, which is the source of fast ions in present day laboratory-scale experiments. Globus-M spherical tokamak (R/a = 0.36/0.24 = 1.5, B_{tor} = 0.4 T, I_p = 0.2 MA, neutral beam injection (NBI) of 0.3-1 MW, 18-30 keV) offers opportunity to study energetic particle behavior and to compare modeling results with the experiments. Globus-M2 (R/a = 0.36/0.24 = 1.5, B_{tor} = 1 T, I_p = 0.5 MA, two NBIs of 1 MW, 18-30 and 20-50 keV) [2], which is under construction now, will expand the scope of the available experimental conditions. The current report continues the series of work aiming 1) to create and test a model that adequately describes the fast ion losses, plasma heating, current generation, yields and spectra of generated neutrons; 2) to verify this model in experiments on Globus-M and Globus-M2; 3) to compare it with results obtained by the other computer codes such as NUBEAM [3].

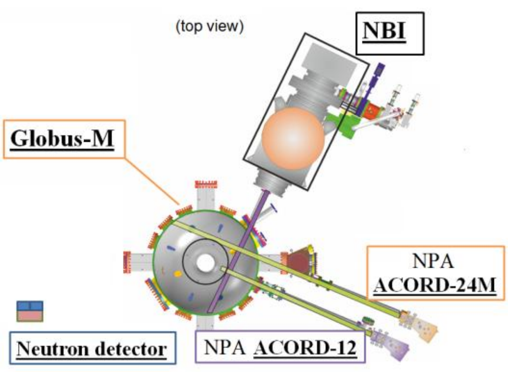

Figure 1. Experimental set-up.

Experimental set-up and main techniques

Experimental set-up is shown in Figure 1. The main used diagnostic tools are two charge exchange (CX) neutral particle analyzers (NPA) and neutron detector. ACORD-12 NPA is used for studying the evaluation of the ion temperature, isotope composition and energy spectrum of the trapped ions. ACORD-24M NPA, which observes plasma with the same

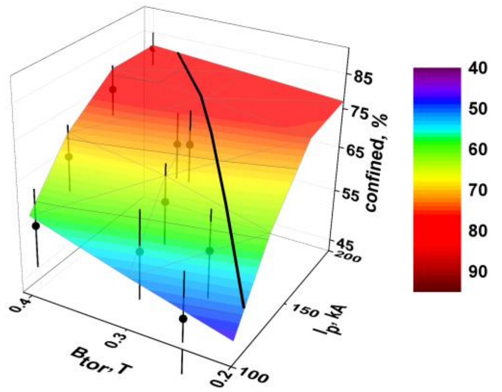

Figure 2. Simulated dependence of the confined fast ion fraction on plasma current and toroidal magnetic field for the 18 keV H NBI (3D surface) and experimental estimates of the percentage of the confined particles (dots).

impact parameter as the NBI, is used for recording of the energy spectrum of the passing particles. Electron temperature and density profiles were measured by means of the Thomson scattering diagnostics. Plasma shape was reconstructed by means of the EFIT code [4] and neutral density distribution was calculated using DOUBLE code. Two codes utilizing different principles were applied for the calculation of the fast ion distribution: the NUBEAM module and the full 3D fast ion tracking algorithm combined with the solution of the Boltzmann kinetic equation [Goncharov P.R. et al. Phys. Plasmas 17 (2010) 112313]. Fast ion tracking algorithm is used to calculate the source function for the Boltzmann equation taking into account direct losses. The Boltzmann kinetic equation describes the ion slowing down. It contains the Landau collision term, pitch angle scattering term, slowing-down losses term and velocity diffusion term.

The influence of the magnetic field and plasma current on fast ion confinement

Parametric dependence of the confinement of fast particles produced by the 18 keV H beam on magnetic field and plasma current was studied in Globus-M. The modeling result obtained by the tracking algorithm is shown as a 3D surface in Figure 2. Experimental estimates are indicated by points with error bars. The experimental border separating the MHD stable region for the set of the performed experiments from the unstable one is drawn as a solid line of constant Ip/B ~ 500 kA/T. The strong variation of direct losses with plasma current is seen. The reason of this lies in the fact that the change in plasma current completely changes orbit shape while the increased magnetic field only makes the orbits more narrow, which is illustrated in figure 3 where orbits calculated by the 3D tracking algorithm are shown.

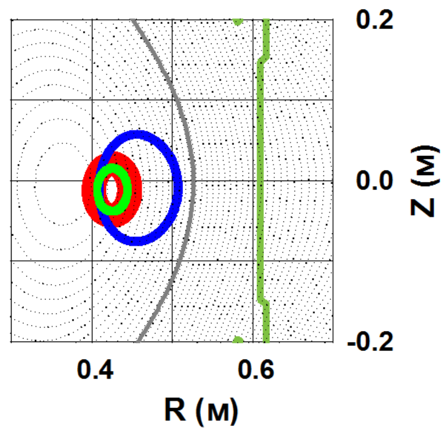

Figure 3. Orbits of the 18 keV H ions ionized in the same point for the case of 200 kA and 0.4 T (green), 105 kA and 0.4 T (blue) and 200 kA and 0.2 T (red).

Counter-NBI

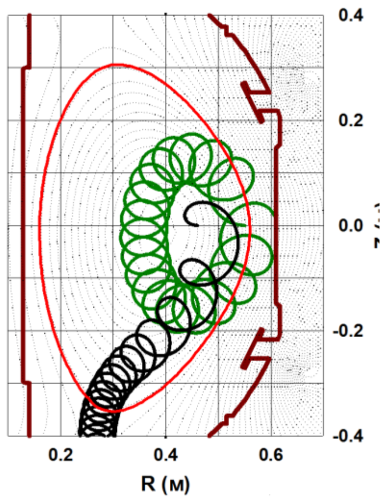

Figure 4. Typical orbit of the lost ion during co- (green) and counter- (black) NBI. Plasma border is shown by the red line.

First experiments on counter-NBI were carried out in the Globus-M spherical tokamak. ELM-free H-mode was obtained. The main feature of these experiments is extremely high first orbit (FO) losses of the fast ions. Orbit modeling shows that even for the case of the 18 keV H NBI they are around 85-95% depending on the experimental conditions. For comparison in the case of the co-NBI FO losses are around 15%. NUBEAM simulations show more optimistic result – FO losses are less than 50%, while total losses are ~ 30%. This significant difference is obviously due to the guiding center approximation used in NUBEAM. Despite the fact that the "generalized" finite Larmor radius correction, adapted for the spherical tokamaks, is incorporated in NUBEAM, nonnegligible difference from the result obtained without approximation by tracking algorithm exists for these specific conditions. It is interesting to note, that orbits of the lost ions during counter-NBI differ from the orbits of co-injected lost ions. While during co-NBI energetic ions which undergone FO losses hit the outer wall, during counter-NBI they get into the divertor region. Typical orbits of the lost ions in co- and counter-NBI cases are shown in Figure 4.

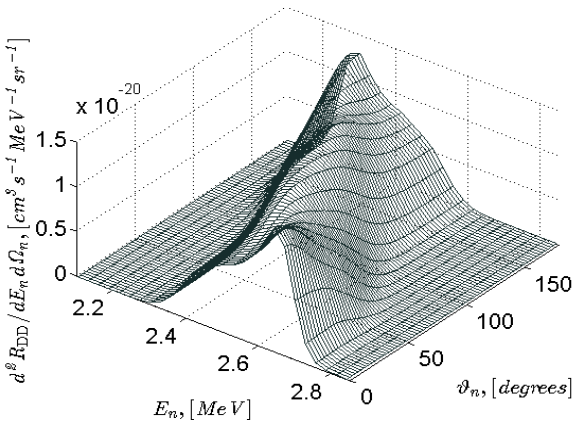

Figure 5. Calculated double differential local rate coefficient of deuterium-deuterium fusion reaction depending on neutron energy and laboratory angle in the center of Globus-M2.

High fast particle losses result in an insignificant ion heating as compared to the case of co-NBI. Only 10-20% ion temperature growth is observed, while during co-injection threefold increase is easily obtained [5]. This fact is consistent with the simulation results. Modeling and experiment did not reveal strong dependence of FO losses on plasma current and inward plasma shift in contrast to the case of the co-NBI [6]. This leads to the fact that in Globus-M2 FO losses during counter-NBI will be around 70% both for the 30 and 50 keV beams. Further 10% FO losses reduction is possible by decreasing beam impact parameter by 4 cm. Despite the fact that fast ion losses during counter-NBI still significant, the full absorbed NBI power will be higher by order of magnitude. It will be up to 0.5 MW for the 2-injector case, which is greater than absorbed NBI power in Globus-M during co-NBI.

Neutron spectra calculations

Since one of the main Globus-M/M2 tasks is the support of the compact neutron sources line, it is important not only to be able to calculate neutron yield, which is routinely done by many computer codes, but also to calculate beam-plasma neutron spectra. Figure 5 shows the energy and angle distribution of the local DD fusion neutron source calculated for the parameters in the center of Globus-M2 plasma column using the formula derived in [7] and a simple analytical model for the anisotropic velocity distribution of fuel nuclei described therein. At the next step, the calculations of expected distributions for the particular observation geometry of a neutron spectrometer on Globus-M2 are planned on the basis of a more profound model.

Conclusions

Investigation of fast ion confinement in Globus-M tokamak was continued. New modeling techniques were developed and successfully applied. Dependence of the direct losses on plasma current and magnetic field was studied. Peculiarities of the energetic particle behaviour during counter-NBI were investigated. Neutron spectrum for the upcoming Globus-M2 was calculated.

Acknowledgements

The work has been carried out on unique scientific device “Globus-M”. N.N. Bakharev, V.K. Gusev, V.B. Minaev, N.V. Sakharov and S. Yu Tolstyakov thank for financial support Ministry of Education and Science of the Russian Federation (Agreement 14.619.21.0001, id RFMEFI61914X0001).

References

[1] Masayuki Ono and Robert Kaita, Physics of plasma 22 (2015) 040501

[2] Gusev V.K. et al. Nucl. Fusion 53, 093013 (2013)

[3] Pankin A. et al. Comp. Phys. Comm. 2004 159 157

[4] Lao L.L. et al. 1985 Nucl. Fusion 25 1611

[5] Bakharev N.N. et al. 2013 TPL 39 1085

[6] Bakharev N.N. et al. Nucl. Fusion 55 (2015) 043023

[7] Goncharov P.R. Nucl. Fusion, 55 (2015) 063012