Fast ion confinement analysis in Globus-M

N.N. Bakharev[1], F.V. Chernyshev[1], V.K. Gusev[1], P. R. Goncharov[2], A.D. Ibliaminova[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], S.Yu. Tolstyakov[1], P.B. Shchegolev[1], G.V. Zadvitskiy[2]

[1] *Ioffe Institute, St. Petersburg, Russia*
[2] *St. Petersburg State Polytechnical University, St. Petersburg, Russia*

Unlike conventional tokamaks, present-day spherical machines suffer from high losses of energetic particles because of the low toroidal magnetic field and relatively small sizes. At the same time good fast ion confinement is an essential requirement for the successful future commercial use of compact fusion neutron sources (CFNS) and two-energy component spherical tokamak-reactors. Losses of the energetic particles will lead to the deterioration of the neutron yield and system efficiency. It is also important that lost particles may damage the plasma-facing materials, making steady state operation of CFNS a challenging problem.

In this paper energetic ion confinement in the compact spherical tokamak Globus-M [1] (R/a=0.36/0.24, B = 0.4 T, I ≤ 250 kA) is discussed. The neutral beam injector (NBI) capable of injecting hydrogen and deuterium at the energy of 18-30 keV is used as the source of fast particles. Due to the relatively low magnetic field and compact geometry of the device, all types of fast ion losses (direct, slow-down due to charge-exchange (CX) and MHD-induced) are significant, making it possible to observe them all in experiment. This fact gives us an opportunity to accurately verify modeling results and to study dependencies of the fast ion losses on different plasma parameters.

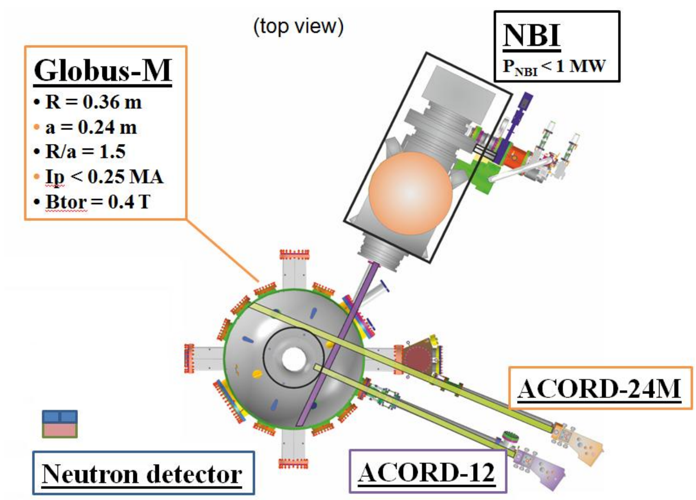

Figure 1. Experimental setup.

The main diagnostics are two neutral particle analyzers (NPA) and the neutron detector – see figure 1. Both NPAs were placed in the equatorial plane of the tokamak. The ACORD-12 NPA line of sight (LOS) was directed perpendicular to the plasma column and the ACORD-24M NPA observed plasma with the same impact parameter as the NBI. Modeling is performed by means of the NUBEAM module [2] and full 3D fast ion tracking algorithm [3] which was designed for the usage in spherical tokamaks, where particle orbits are not well described by the guiding center or drift approximation [4]. This code calculates the ionization profile of the beam, thereafter it solves the equation of particle motion in electric and magnetic field to figure out if particle undergoes first orbit losses. Ion slowing down is described by the Boltzmann kinetic equation with Landau collision term [5] including the velocity diffusion term and losses term. This method differs from the statistical Monte-Carlo method used for slowing down process in NUBEAM, so comparison of various approaches is possible. Magnetic field was reconstructed by the EFIT code [6]; electron density and temperature profiles was measured by the Thomson scattering diagnostic; central ion temperature is provided by the NPA measurements; neutral density distribution is calculated by the DOUBLE code.

High fast ion losses were observed in Globus-M during experiments with 18-26 keV H and D injection into D plasmas. It was found, that in different regimes different types of losses prevail. For 26 keV D injection ("bad" confinement case) the first orbit losses dominate. Note, we consider that not only particles, which hit the wall, contribute to the first orbit losses, but also particles with orbits intersecting last closed magnetic surface: these ions undergo CX losses in a short period of time as compared to the slowing-down time. For 18 keV H injection ("good" confinement case) the CX losses during slowing-down and first orbit losses are comparable. These results are confirmed by the different types of modeling mentioned above. For the CFNS the slowing-down losses are less important because of the two main reasons. First, the fusion reaction rate is strongly dependent on fuel nuclei energy distribution, so the fastest ions will make the major contribution to the neutron yield. Second, the CX rate drops significantly for the energies higher than several tens of keV, while the planned beam energy for CFNS is sufficiently higher.

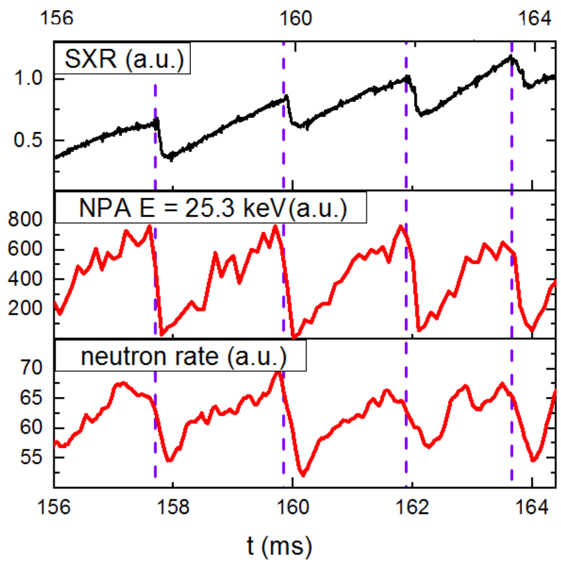

Figure 2. Correlation of sawtooth oscillations with neutron rate and NPA fluxes.

Sawtooth oscillations increase the fast ion losses up to 25%. Variation of the neutron yield and NPA flux of 25 keV D atoms (this energy is close to the NBI energy) during the sawtooth oscillations is shown in figure 2. However, if injection energy and power are low (~18 keV and 300 kW), oscillations influence on fast ion confinement is insignificant. In the absence of sawtooth oscillations, when the injection energy is high enough, the toroidal Alfven eigenmodes may appear [7], further increasing losses by up to 25%.

A way to improve the fast ion confinement and thereby essentially increase the neutron rate and ion temperature was found [8]. It is the inward shift of the plasma column, which increases the distance between the wall and the plasma boundary at the low-field side. And, vice versa, an outward shift results in additional fast ion losses. There are three main reasons for this improvement. Firstly, because of the more tight magnetic configuration, the fast ion orbits shift inwards, leading to lower direct and CX losses. The higher the injection energy and power are, the greater the change is. Secondly, the density profiles change their shape, contracting inwards, amplifying first effect. Thereby, beam atoms, ionized in the region with higher magnetic field, have more compact orbit. Thirdly, sawtooth-induced losses decrease, which is very important for ions with high energies (~ 25 keV). Due to plasma shift total loses decrease from 80% to 65% for the main energy component of the 26 keV D beam and from 50% to 40% for the main energy component of the 18 keV H beam.

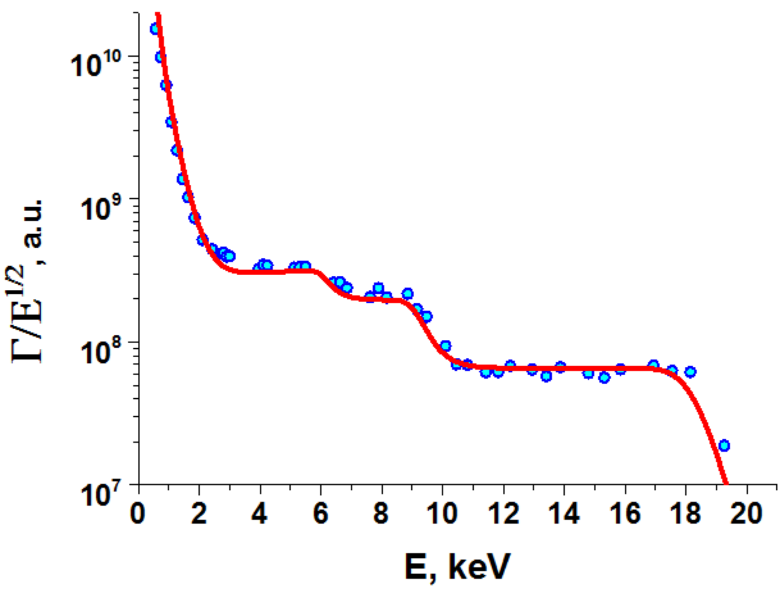

Figure 3. CX spectrum, measured by NPA (dots) and modeled (line).

Improvement in confinement is confirmed by modeling mentioned above. In the absence of sawtooth different types of simulations are in good agreement with each other and experiment. As an example, figure 3 shows the CX spectrum measured by the ACORD-24M NPA and the spectrum, calculated by orbital modeling with subsequent solution of the Boltzmann kinetic equation, followed by chord integration taking into account the rates of elementary atomic processes and the geometry of the NPA LOS. However, the discharges with sawtooth oscillations need a more detailed study. For this purposes modeling should be modified and NPA diagnostics should be rearranged in such a way that permits to change its LOS.

Summarizing performed investigations we can state, that total power losses of the main neutral beam energy component decreases with its energy and vary from 40% (for 18 keV H beam and shifted inside plasma column) up to 90% (for 26 keV D beam and shifted outside plasma column).

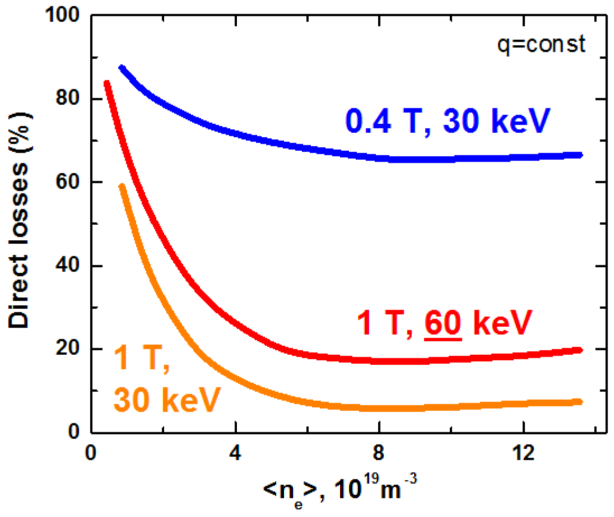

Figure 4. Dependence of the direct losses of the deuterium beam on the line-averaged density in Globus-M (0.4 T) and Globus-M2 (1T) for different NBI energies.

In Globus-M2 [9] toroidal magnetic field and plasma current will be increased up to 1 T and 500 kA respectively. Modeling shows that fast ion losses will be decreased significantly so it will be possible to use injection of 60 keV D atoms. Dependence of the direct losses (which are most important for the higher energies) on the line-averaged plasma density for 30 keV and 60 keV D NBI in Globus-M and Globus-M2 is shown in figure 4. For the main energy component of 30 keV beam the direct losses will be decreased by a factor of 10 as compared to the Globus-M tokamak. Direct losses for the 60 keV NBI will be tolerable (close to 18 keV H beam losses in Globus-M).

Results of this report have been obtained by means of the unique scientific device Globus-M spherical tokamak.

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