Calculations of anisotropic distribution function of fast particles in plasma of the Globus-M spherical tokamak using the NUBEAM code

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Abstract. The results from calculations of the anisotropic fast particle distribution function in the Globus-M/M2 spherical tokamaks are presented. The calculations were performed using the NUEBAM code, the reasons for the anisotropy occurrence are discussed (injection geometry, low toroidal magnetic field and plasma current, presence of neutral particles). It is shown that the anisotropy decreases with increasing toroidal magnetic field and plasma current: the density of the slowed down fast ions with energies of $E < 4$ keV almost doubles and the averaged perpendicular velocity of fast ions increases.

1. Introduction
The NBI-induced distribution function of fast particles is anisotropic in the velocity space. It can be the reason for stabilization [1] or destabilization of the ballooning plasma instabilities [2]. The peeling-ballooning mode (one of the possible triggers of ELMs) is unstable in the Globus-M tokamak plasma [3], due to the ballooning mode destabilization. The effect of fast particles on this mode occurs due to fast particle contribution to the plasma pressure and anisotropy of their distribution function. These studies are important, since the Globus-M tokamak (in which the peeling-ballooning mode is unstable) is now being upgraded to the Globus-M2 tokamak, in which the confinement of the fast particles and the bulk of plasma will be considerably improved.

2. Fast particle distribution function in plasma of the Globus-M spherical tokamak
In this work, the anisotropic fast particle distribution functions are calculated for the Globus-M [4] and the Globus-M2 [5] spherical tokamaks, which are characterized by the high heating power density (up to 2 and 5 MW/m$^3$, respectively). The Globus-M is a compact spherical tokamak with the following parameters: the aspect ratio is $R/a \sim 1.5$ (the major radius is $R = 0.36$ m, and the minor radius is $a = 0.24$ m) and the vertical elongation is $k \sim 1.8$–2. The experiments described below (#37062, #37063, 37065-37067 [6]) were performed in deuterium plasma in the lower null magnetic configuration with a toroidal magnetic field of $B_T = 0.5$ T and a plasma current of $I_p = 0.225$ MA. The additional heating was performed using the neutral beam injector with a power of 0.65 MW and...
a deuterium beam energy of $E_b = 26$ keV. The injection line is in the equatorial plane and it is tangentially directed with respect to the torus axis; the impact parameter is 0.3 m. The beam has the Gaussian shape; its widths at half heights in the horizontal and vertical planes are 12 and 24 cm, respectively.

Calculations of the fast particle anisotropic distribution function were performed using the NUBEAM code involving the Monte-Carlo simulations [7]. Only classical effects were included in the model, without accounting for the anomalous diffusion and instabilities.

Figure 1 presents the typical fast particle distribution over energies and cosines of the pitch angle $\theta$ (angle between the fast particle velocity vector and the magnetic field vector). Three main components of the beam can be distinguished, which have the following energies: $E_b/3 = 9$ keV, $E_b/2 = 13$ keV, and $E_b = 26$ keV. The most part of the fast particles are in the region of positive pitch-angle cosines. The anisotropy of the slowed down ions with energies of $E < 4$ keV is not so pronounced; there is a small number of particles with negative pitch angle cosines.

![Figure 1. Typical fast ion distribution function in plasma of the Globus-M tokamak.](image)

3. The reasons for the fast particle distribution function anisotropy

There are several reasons for the strong anisotropy of the fast particle distribution function in plasma of the Globus-M tokamak. The first and the main reason is the injection geometry: the NBI injection line is in the equatorial plane of the torus and it is directed tangentially with respect to the torus axis. This NBI geometry is typical of tokamaks. Due to the injection geometry, the distribution function of ions (produced as a result of ionization and charge exchange reactions with the NBI-injected atoms) is anisotropic. Figures 2a and 2b present the ratio of the fast particle parallel velocity to the total velocity along the injection line and the histogram of a number of ions with different ratios of the parallel velocity to the total velocity, respectively. Obviously, the most part of ions moves almost parallel to the magnetic field lines.

The second reason for anisotropy of the fast ion distribution function is the relatively low magnetic field and the compact geometry of the Globus-M tokamak. These design features of the Globus-M tokamak result in the high losses of particles having high velocity component perpendicular to the magnetic field.

The third reason is the development of various MHD instabilities which resulted in the fast ion losses. Previously, the sawtooth oscillations and Alfven instabilities were discovered in plasma of the Globus-M tokamak, which resulted in the losses of fast ions [8–10]. We note that, in a number of experiments, the effect of these instabilities results in the low fast ion losses due to the considerable angular redistribution of particles and the corresponding reduction of the anisotropy.
Figure 2. a) Ratio of the fast particle parallel velocity to the total velocity of ions, produced as a result of ionization and charge exchange reactions with the NBI-injected atoms. Top view.
b) Histogram of a number of ions with different ratios of the parallel velocity to the total velocity for the fast ions, produced as a result of ionization and charge exchange reactions with the NBI-injected atoms.

The fourth reason for the anisotropy is the effect of neutral particles. The relatively small distance between the chamber wall and plasma and, hence, the high neutral density at the plasma edge lead to the additional losses due to the charge-exchange reactions of the NBI fast particles with neutrals.

4. The effect of the toroidal magnetic field and plasma current on the anisotropy of the fast particle distribution function

The Globus-M [4] tokamak upgrade is completed. As a result, a considerable improvement in the fast particle confinement is expected. To estimate the improvement of the fast particle confinement in the Globus-M2 tokamak, in calculations of the magnetic equilibrium of the Globus-M tokamak \( (B_T = 0.5 \, \text{T and } I_p = 0.225 \, \text{MA}) \), the toroidal magnetic field and the plasma current were doubled; the temperature and density profiles, and other parameters remained unchanged.

The fast particle confinement is considerably improved in the shot with the increased toroidal magnetic field and plasma current (Figure 3a) as compared to the basic shot (Figure 1). It can be seen that the distribution of the slowed down ions is less anisotropic, especially the distribution of ions with energies of \( E < 4 \, \text{keV} \) (their density almost doubles), and the density of ions with negative pitch-angle cosines increases by more than an order of magnitude (Figure 3b).

Figure 3. a) Fast particle distribution function obtained at the doubled toroidal magnetic field and plasma current. b) Comparison of the dependences of the distribution function value at energy of \( E = 4 \, \text{keV} \) on the pitch-angle cosine obtained in two cases: the basic shot (red line) and the shot with the doubled toroidal magnetic field and plasma current (blue dotted line).
Figure 4. Averaged parallel fast particle energy (a) in the basic shot, (b) in the shot with doubled toroidal magnetic field and plasma current; averaged perpendicular fast particle energy (c) in the basic shot, (d) in the shot with doubled toroidal magnetic field and plasma current. All figures have the same energy scale.

Figure 4 illustrates the effect of changing the anisotropy of the distribution function by the example of the parallel and perpendicular fast ion velocities. It can be seen that the first orbit losses decrease with increasing toroidal magnetic field and plasma current. This results in an increase in the averaged perpendicular fast ion velocity. And the averaged parallel fast ion velocity decreases due to an increase in density of the slowed down ions.

5. Conclusions
The fast particle distribution function in plasma of the Globus-M spherical tokamak is anisotropic. It is due to the fast ion losses and injection geometry. High particle losses in plasma of the Globus-M tokamak occur due to the relatively low magnetic field, the compact tokamak geometry and high neutral density at the plasma edge. These factors cause the considerable first orbit and shine-through losses, the charge exchange losses during the slowing down of ions and the MHD-induced losses. Fast particle confinement considerably improves at the increased toroidal magnetic field and plasma current, especially for the particles with high velocity perpendicular to the magnetic field, and the distribution function of fast ions becomes more isotropic.
At equal absorbed NBI powers, the effect of anisotropy of the fast ion distribution function on the plasma stability will be considerably less in the Globus-M2 tokamak as compared to the Globus-M tokamak due to the improvement of the fast particle confinement. On the other hand, an increase in the additional heating power and the improvement of the fast particle confinement will lead to an increase in the pedestal pressure, and destabilization of the peeling-ballooning modes, as compared to the Globus-M calculations [3]. The effect of the pressure anisotropy on the plasma stability during the ELM events is not clear, and further calculations are required.

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