Effect of collisionality on the microinstabilities in the Globus-M spherical tokamak

E O Kiselev1, N N Bakharev1, V V Bulanin2, V K Gusev4, N A Khromov4, G S Kurskiev1, V B Minaev1, I V Miroshnikov1, M I Patrov1, A V Petrov2, Yu V Petrov4, N V Sakharov1, P B Schegolev1, A Yu Telnova1, V A Tokarev1, S Yu Tolstyakov1, E A Tukhmeneva1 and A Yu Yashin3

1 Ioffe Institute, St. Petersburg, Russia
2 SPbPU, St. Petersburg, Russian Federation
3 Email: kiselev.eo@mail.ioffe.ru

Abstract. Simulations of the microtearing instability developing in plasma of the Globus-M spherical tokamak were performed using the GENE gyrokinetic code in the flux-tube linear approximation mode. Under the effect of the instability, the magnetic islands form on the scale of the ion Larmor radius, and the magnetic field fluctuations occur that generate electron heat fluxes. The ion heat fluxes as well as the fluxes associated with the electrostatic fluctuations are negligible. The maximum growth rate of the microtearing instability is reached at a collision frequency within the experimental range of the collision frequency variation, within which the $B_T \times \tau_E \propto \nu^*^{-0.4\pm0.1}$ scaling calculations were performed [1]. In similar calculations performed at the MAST tokamak, the growth rate decreases with decreasing collisionality in the entire range of the collision frequency variation, within which the $B_T \times \tau_E \propto \nu^*^{-0.82}$ scaling calculations were performed [2]. This can explain why the dependences of energy confinement time on the collision frequency obtained for the MAST&NSTX and the Globus-M tokamaks are different.

1. Introduction
One of the main reasons for the heat and particle losses in tokamaks is the development of various plasma microinstabilities, which generate the anomalous heat and particle fluxes. In experimental studies of the heat fluxes dynamics on both conventional and spherical tokamaks, it is convenient to study the dependences of the energy confinement time on various plasma parameters, such as: the toroidal beta, the normalized Larmor radius $\rho^*$, the collisionality $\nu^*$, the aspect ratio $A$, the elongation $\kappa$, etc. It has been found that, in the spherical tokamaks, the energy confinement time $\tau_E$ stronger depends on the collisionality than in large aspect ratio tokamaks: in the MAST, $B_T \times \tau_E \propto \nu^*^{-0.82}$ [2]; in the NSTX, $B_T \times \tau_E \propto \nu^*^{-0.97}$ [3]; and in the Globus-M, $B_T \times \tau_E \propto \nu^*^{-0.4\pm0.1}$ [1]. However, the ITER collisionality scaling ($B_T \times \tau_E \propto \nu^*^{-0.01}$ [4]) has the weaker dependence.

The development of microinstabilities can be one of the possible explanations for the improvement of confinement with decreasing collisionality. In contrast to the energy confinement time $\tau_E$, the growth rates of microinstabilities decrease with decreasing collisionality. The DTEM (dissipative trapped electron mode) [5] and the microtearing instability [2, 6] can be the examples of such instabilities. The recent linear gyrokinetic calculations of the spherical tokamak equilibria suggest that these devices are subjected to the development of instabilities causing the magnetic reconnection on the scale of the ion gyro-radius. These so-called microtearing modes have been observed in the NSTX [6].
and MAST [2] tokamaks, and they turned out to be unstable in the regimes with improved confinement.

Previously, it was suggested that the ion temperature gradient (ITG) driven instability was the main source for occurrence of the heat fluxes in the conventional tokamaks. However, the experimental data suggest that, in the H-mode plasmas of the ST tokamak [2, 3, 8], the electron heat transport is dominant (the ion heat transport is almost neoclassical [9]). This is not typical of the ITG mode. The electron drift along the stochastic magnetic field lines, caused by the development of microtearing instabilities, can be the explanation for the electron heat transport.

In this paper, the simulations were performed of the microtearing mode development in the core plasma of the Globus-M compact spherical tokamak. The following parameters were used in simulations: the inverse aspect ratio was $\varepsilon = 0.24$ m / 0.36 m = 0.66, the toroidal magnetic field was $B_T = 0.4$–0.5 T, the plasma current was $I_p = 0.18$–0.25 MA, the averaged electron density was $\langle n_e \rangle = (1–8) \times 10^{19}$ m$^{-3}$, and the NBI power was $P_{\text{NBI}} \leq 1$ MW.

2. Simulations

Gyrokinetic simulations of the microtearing instability development in the H-mode Globus-M plasma have been performed using the GENE gyrokinetic code [12] in the flux-tube linear approximation mode. The unperturbed distribution function was assumed to be Maxwellian. All electromagnetic effects were included in the model: the perpendicular and parallel magnetic fluctuations were considered. According to the $\partial f$ method, the distribution function was represented as a sum of the static Maxwellian background $F_0$ function and the small fluctuating part $f_i$. Three particle species were considered by default: electrons, thermal deuterium ions and carbon ions. In the GENE simulations, collisions are modeled using the linearized Landau-Boltzmann operator. The magnetic geometry fits the analytical Miller form [13].

![Figure 1](image)

**Figure 1.** (a) Normalized growth rate $\gamma(a/c_s)$ and (b) frequency $\omega(a/c_s)$ as functions of wave number $k_s \rho_i$ ($\rho_i = \zeta / \Omega_i$, $\Omega_i$ is the Larmor frequency).

Simulations of instabilities were performed for shot #31554 at $r/a = 0.5$ using the collisionisloality scan in the H-mode; the more detailed description can be found in [1]. Basing on the ASTRA calculations (1.5-dimensional transport code) [14], the input parameters for modeling were obtained: the magnetic geometry data and the kinetic plasma parameters are present in Tables 1 and 2, respectively.

In the tables, $q$ is the safety factor, $s$ is the magnetic shear, $a$ and $R_0$ are the tokamak minor and major radii respectively, $a/R_0$ is the local inverse aspect ratio, $\kappa$ is the elongation, $\delta$ is the triangularity, $L_s = -[\partial (\ln n) / \partial r]^{-1}$ and $L_T = -[\partial (\ln T) / \partial r]^{-1}$ are the density and temperature gradients, respectively, $T$ is the temperature and $n$ is the density. Dimensionless parameters are the toroidal beta $\beta_T = 8 \pi n T_s / n n_T$, $B_T^2 = 0.06$, $\alpha_{\text{min}} = -q' R (d / dt) R$, the frequency of electron-ion collisions $\nu_{ei} = \pi Z^2 e^2 n_i \ln \Lambda / 2 m_e T_e^{\frac{3}{2}} = 1.3 a / c_s$, and $\ln \Lambda = 24 + \ln \left( \sqrt{10^3 n_i / 10^3 T_e} \right)$ [12].
Table 1. Input data on the magnetic geometry.

| q     | s     | a_{MHD} | R_0   | a    | a/R_0 | κ    | δ    |
|-------|-------|---------|-------|------|-------|------|------|
| 1.38  | 1.23  | 0.56    | 0.32  | 0.2  | 0.31  | 1.5  | 0.06 |

Table 2. Input data on plasma parameters.

|        | a/L_n | a/L_T | n, 10^{19} m^{-3} | T, keV |
|--------|-------|-------|-------------------|--------|
| Electron | 0.83  | 2.3   | 4.2               | 0.41   |
| Deuterium | 0.55  | 2.1   | 2.31              | 0.41   |
| Carbon  | 0.7   | 2.1   | 0.315             | 0.41   |

Figure 1 shows the growth rate \( \gamma(a/c_s) \) (a) and the frequency \( \omega(a/c_s) \) (b) (normalized to the ratio of the speed of sound \( c_s = (T_e/m_e)^{0.5} \) to the minor radius \( a \)) as functions of the wave number \( k_s \), normalized to \( 1/\rho_s \), where \( \rho_s = c_s/\Omega_s \), and \( \Omega_s \) is the Larmor frequency. The frequencies of instability development range from 0.42 to 1.4 MHz, the wave numbers range from 13.6 to 146 m^{-1}.

This tearing instability can be characterized by the parallel vector of the magnetic field potential \( A_{||} \). \( A_{||} \) is the even function of the ballooning angle \( \theta \), and it mainly concentrates near \( \theta = 0 \). In this case, the electrical field potential \( \Phi_0 \) is the odd function of the ballooning angle \( \theta \) (Figure 2), and the potential broadens along the field lines due to the fast motion of electrons.

Figure 2. (a) Electrical field potential \( \Phi_0 \) and (b) parallel vector of magnetic field potential \( A_{||} \) as functions of the ballooning angle.

The GENE code used the flux tube simulation domain in the form of a long thin tube parallel to the magnetic field lines. The motion along the tube is described by the \( \theta \) angle; \( x \) is the radial coordinate and \( y \) can be considered as a marker of the magnetic field lines. The Poincare plots can be obtained by cutting the magnetic field lines in the flux tube at the constant \( \theta \) angle.

Poincare plots were calculated at \( \theta = 0 \) for a single harmonic mode with \( k_s\rho_s = 0.4 \). Figure 3 represents the magnetic island structure and the perturbations of the magnetic field lines, causing the enhanced electron transport. In this case, the electron heat flux due to the electrostatic fluctuations, calculated in the linear approximation, is 30 times smaller, than the electron heat flux, caused by the electromagnetic fluctuations. The heat fluxes transported by deuterium and carbon ions are negligible, as compared to the electron transport.

3. Collisionality scan of the microtearing mode

One of the distinguishing features of the microtearing mode is the fact that its growth rate is maximal at some finite value of the electron collisionality. Figure 4 shows the growth rates \( \gamma(a/c_s) \) of the harmonics \( k_s\rho_s = 0.4 \) (harmonic with the maximum growth rate in Figure 1) and 0.2 as functions of the electron-ion collision frequency \( \nu_{ei} \) (other input parameters being fixed). At low collision
frequency (less than $v_{ci} = 0.015(a/c_s)$), the ITG mode develops, and its growth rate decreases with increasing collision frequency. In the frequency range of $v_{ci} = 0.015(a/c_s) - 0.11(a/c_s)$ no instabilities are developing (growth rates are negative). In the frequency range of $v_{ci} = 0.11(a/c_s) - 14.4(a/c_s)$, the microtearing instability starts to develop, reaching the maximum at $v_{ci} = 2.7(a/c_s)$. This peak is close to the experimental value of $v_{ci} = 1.3(a/c_s)$ (shot #31554). The calculations of $B_T \times \tau_E \propto \nu^{* -0.4\pm0.1}$ scaling were performed in the frequency range of $v_{ci} = 0.5(a/c_s) - 11.7(a/c_s)$, which corresponds to the entire domain of existence of the unstable microtearing mode in Figure 4.

4. Conclusions
The microtearing mode is unstable in the H-mode plasma of the Globus-M spherical tokamak. The microinstability causes the magnetic reconnections on the scale of the ion gyro-radius and the magnetic field perturbations that generate the electron heat fluxes, while the heat fluxes due to the electrostatic fluctuations are negligible. The growth rate of the microtearing instability is maximal within the range of collision frequency variation used for the $B_T \times \tau_E \propto \nu^{* -0.4\pm0.1}$ scaling calculations [1]. The similar calculations performed at the MAST ($B_T \times \tau_E \propto \nu^{* -0.82}$) and the NSTX ($B_T \times \tau_E \propto \nu^{* -0.97}$) tokamaks showed that the experimental values of the collision frequency corresponding to the maximum instability growth rate fall into the frequency range, in which the growth rate decreases with decreasing of collision frequency. This fact can explain why the dependences of energy confinement time on the collision frequency obtained for the MAST&NSTX and the Globus-M tokamaks are different.

The similar calculations for the MAST ($B_T \times \tau_E \propto \nu^{* -0.82}$) and the NSTX ($B_T \times \tau_E \propto \nu^{* -0.97}$) tokamaks showed that the experimental values of the collision frequency corresponding to the maximum instability growth rate fall into the frequency range, in which the growth rate decreases with decreasing of collision frequency. This fact can explain why

\[ \gamma(a/c_i) \text{ as functions of collision frequency } v_{ci}(a/c_s) \text{ for harmonics } k_x \rho_i = 0.4 \text{ and } 0.2. \]
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