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Simulations of peeling-ballooning modes in the Globus-M tokamak

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Abstract. Analysis of stability of the peeling-ballooning modes in the edge plasma of the Globus-M tokamak is presented. Studies were performed using the ideal 3D MHD code written in the BOUT++ framework. The edge localized modes which are frequently observed in the Globus-M plasma could be described using MHD theory. It was found that the parameters of the Globus-M edge plasma are in the range of stability for the peeling-ballooning modes. The instability modes with a toroidal number of $n = 12$ and typical distances between filaments of approximately ~ 12 cm were found to be the most unstable. This statement agrees with the Doppler backscattering measurements. It was also considered whether the plasma in the Globus-M2 tokamak will be stable against the PB instability.

1. Introduction

Suppression of the edge localized modes (ELMs) in the regimes with improved confinement is one of the most challenging problems in the tokamak physics. The ELMs limit the pedestal parameters and can cause intensive erosion of the first wall. For this reason, these events are scrupulously investigated in many modern tokamaks. Studies show, that the ELMs development is accompanied by the growth of instabilities, which could manifested themselves as the edge localized filamentary structures [1, 2]. Simulations are an important tool in research of the edge instabilities. The performed studies of the ELMs and filaments [3] show that these events can occur as a result of the peeling-ballooning (PB) modes. MHD simulations make it possible to identify the instability types and to predict the edge plasma stability in the next step fusion devices.

In this paper, we present the simulation results for the MHD instabilities development in the edge plasma of the Globus-M tokamak [4] and estimate the possible plasma pedestal parameters in the Globus-M2 tokamak which is the next step spherical tokamak with high toroidal magnetic field [5].

2. ELMy regimes in the Globus-M

H-mode is the usual operation regime of the Globus-M tokamak, which is characterized by moderate densities in both ohmic (OH) and neutral beam injection (NBI) plasma heating regimes [6].



Typical ELMy discharge parameters are as follows: aspect ratio is $a/R = 0.24 \text{ m}/0.36 \text{ m} = 0.66$, the toroidal magnetic field is $B_T = 0.4\text{--}0.5 \text{ T}$, the plasma current is $I_p = 0.18\text{--}0.25 \text{ MA}$, the average electron density is $\langle n_e \rangle = (1\text{--}8) \cdot 10^{19} \text{ m}^{-3}$, and NBI heating power is $P_{\text{NBI}} < 1 \text{ MW}$. The key parameters of a usual ELMy discharge in deuterium with the lower null magnetic configuration and additional NBI heating are shown in Figure 1. The L–H transition occurs at the 162 ms, just after switching on the NBI heating. The ELMs are clearly visible as the bursts of D_α emission during operation in the H-mode, which vanish after the H–L transition. In [7], the filamentary structure of the instability, which develops in the edge plasma of the Globus-M, was investigated using the Doppler backscattering diagnostics (DBS). The measurements show that the ELM filament structure can be characterized by the quasi-toroidal mode numbers in the range of $n = 1215$ and it was observed in the radial range between $R = 53.1 \text{ cm}$ and $R = 58.6 \text{ cm}$.

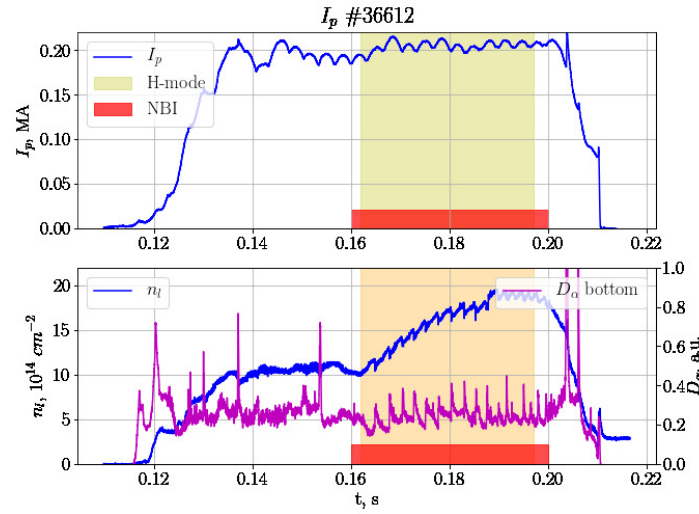


Figure 1. Plasma parameters in discharge #36612: (I_p) plasma current, (n_l) chord-integrated density, and (D_α) emission from the divertor region.

The Thomson scattering (TS) and the probe diagnostics provided the electron temperature T_e and density n_e profiles. The n_e and T_e profiles for $\tilde{L}$ and $\tilde{H}$ modes are presented in Figures 2 and 3, respectively. The probe measurements performed in the scrape-off-layer show that there is almost no difference between the n_e and T_e profiles in the $\tilde{L}$ and $\tilde{H}$ modes. However, the plasma parameters

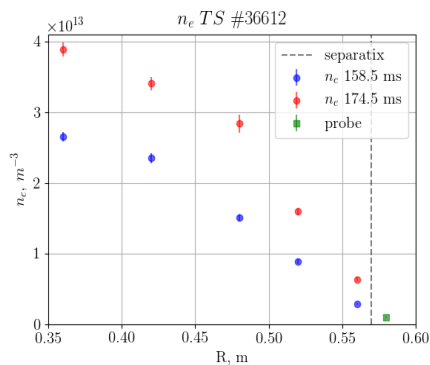


Figure 2. Density profiles n_e before and during NBI in shot #36612.

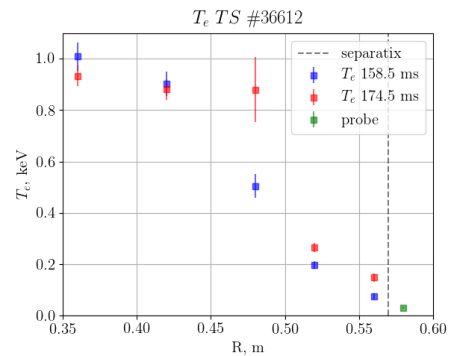


Figure 3. Temperature profiles T_e before and during NBI in shot #36612.

inside the separatrix are different in the $\tilde{L}$ and $\tilde{H}$ modes. After the NBI switching on, the density n_e and temperature T_e rise at the edge, which causes an increase in a pedestal pressure at least by a factor of 2.

This could result in destabilization of the PB modes in the edge plasma. In the H-mode, the profiles shown in Figures 2 and 3 were measured during time intervals between the ELMs. These profiles were used to approximate the background pressure profile in the MHD simulations.

3. MHD simulations of the edge plasma stability

The edge plasma stability against the PB modes development in the Globus-M tokamak was studied using the BOUT++ framework capable of solving the shear-Alfven equations [8] on the 3D grid. Simulations were performed in the linear approximation with the restricted number of high- n toroidal modes ($n < 16$).

We assume $P_i = P_e$ because the collision frequencies in the cold edge plasma are high. Thus, we could believe that the plasma pressure is the doubled electron pressure. The experimental pedestal profiles were approximated by hyperbolic tangential function:

$$p(\psi) = p_{\text{MAX}} \times (\tanh([\Psi_{\text{SHIFT}} - \psi]/\alpha) + 1)$$

where p_{MAX} is pressure at the pedestal top, α is the pedestal width, Ψ_{SHIFT} is the pedestal flux coordinate, and ψ is the current flux coordinate.

The magnetic configuration obtained using the EFIT equilibrium reconstruction [9] was converted by pyGridGen tool to 2D grid in order to use it in the BOUT++ simulations [10]. The bootstrap current density profile was calculated using the Sauter equations [11]. The ohmic current density was calculated using the ASTRA code [12]. The typical bootstrap current density ($j_{\text{BS}} \sim 5 \text{ kA/m}^2$) was not less than the pedestal ohmic current density ($j_{\text{BS}} \sim 4 \text{ kA/m}^2$). The pressure (p_{MAX}) and the profile width (α) were varied in the ranges from 0.5 to 8 mbar and from 0.03 to 0.11, respectively.

Computational domain (in flux coordinates) covers approximately $\sim 1/8$ of the tokamak cross section ($\psi = 0.75\text{--}0.98$) that corresponds to only $\sim 3 \text{ cm}$ due to the high magnetic shear. Though the computational domain is small, its width is larger than 10 ion Larmor radii. The 2D structure of the pressure disturbance of the most unstable PB mode is shown in Figure 4. It can be seen, that the filamentary structures form on the low field side, in the region with unfavorable curvature of the magnetic field lines. The instability mode structure corresponding to the toroidal number $n = 12$ with typical distance between filaments of $\sim 12 \text{ cm}$ was found to be the most unstable. This result is in good agreement with the DBS measurements presented in [7, 13] and it can indicate destabilization of the ballooning branch of the instability.

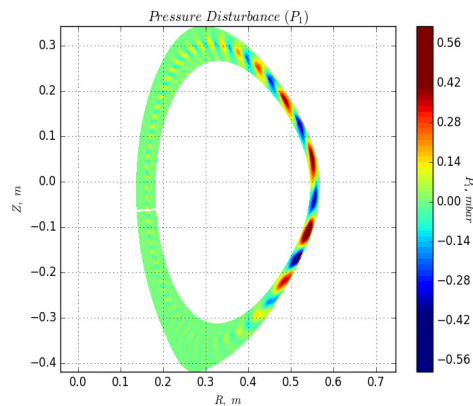


Figure 4. Pressure disturbance calculated for the most unstable PB mode ($n = 12$). [$p_{\text{MAX}} = 7 \text{ mbar}$, $\alpha = 0.07$]

Growth rates of the PB mode calculated for different pressures (p_{MAX}) and profile widths (α) are shown in Figure 5. The red and blue colours correspond to the positive growth rates of the most unstable PB mode and the stable region, respectively. The obtained diagram makes it possible to analyse and predict the edge MHD stability in

the Globus-M facility. The grey area marks the L-mode pedestal parameters, which are in the stable region. The rose area marks the H-mode pedestal parameters, which are near the boundary of unstable region.

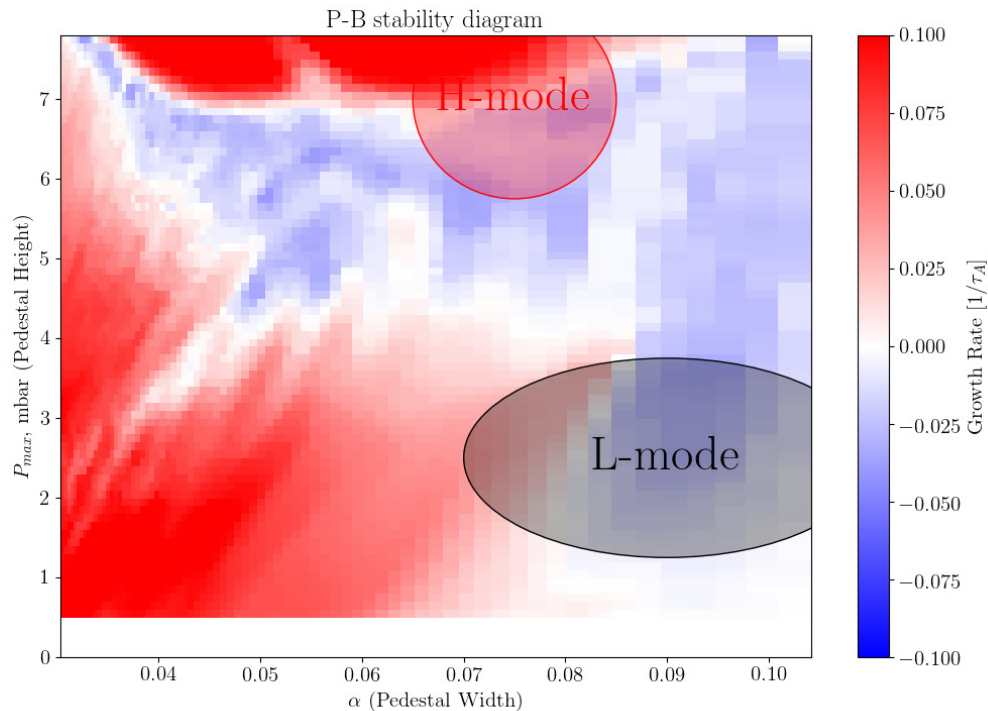


Figure 5. Growth rates of the PB mode as a function of pressure (p_{MAX}) and the pedestal width (α). Magnetic configuration corresponds to 175 ms of shot #36612; (red and blue colours mark the unstable and stable regions, respectively).

4. Conclusions

Simulations of the PB mode development in the edge plasma of the Globus-M tokamak were carried out using the BOUT++ framework. These simulations show that the ELMy edge plasma in the Globus-M tokamak is on the boundary of a stable region. With increasing pressure, the PB modes become unstable due to the ballooning branch destabilization. Critical pressure in the pedestal could be reached either during the natural growth of stored plasma energy or/and it can be triggered by the MHD disruptive events in the core plasma. The PB modes do not actively develop in the L-mode due to considerably lower pressures and wider pedestal parameters.

The pedestal pressure predicted for the Globus-M2 tokamak is approximately ~ 4 times higher [5] than that in the Globus-M, thus the ballooning branch is likely to be unstable. The further analysis of the Globus-M2 edge plasma including the gyrokinetic simulations of electromagnetic instabilities is currently in progress.

Acknowledgments

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