Influence of increased magnetic field on Alfvén eigenmodes on upgraded spherical tokamak Globus-M2

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Abstract. During modernization of the Globus-M tokamak, toroidal magnetic field and plasma current were increased, and a number of diagnostics were upgraded, which made it possible to study phenomena associated with the excitation of Alfvén waves in a spherical tokamak in a wider range of plasma parameters. In the experiments with neutral beam injection, the dependences of fast particle losses initiated by the toroidal Alfvén eigenmodes (TAE) on their magnitude in the magnetic field range of 0.4 – 0.7 T and currents of 180 – 330 kA were acquired. Resulting dependences confirm previously obtained results and indicate a decrease in losses with increasing magnetic field and plasma current. At the same time, a number of new phenomena, that have never been observed on Globus-M were detected. In experiments with neutral beam injection at the current ramp up stage, Alfvén cascades (AC) in the frequency range of 100 – 300 kHz were observed for the first time. By means of the Doppler backscattering diagnostics (DBS), it was shown that ACs are localized closer to magnetic axis unlike TAE. Also, during low hybrid wave current drive (LHCD) experiments, global Alfvén eigenmodes (GAE) were detected at a frequency close to 1 MHz, apparently driven in the resonance with runaway electron beam. Detected global eigenmodes are also able to arise in ohmic discharges, however, their magnitude is lower.

1. Analysis of fast particle losses

Toroidicity-induced Alfvén eigenmodes (TAE) are being observed on Globus-M [1] tokamak during a long period of time [2, 3] in the experiments with neutral beam injection. These modes represent themselves as short-time magnetic field perturbations measured by magnetic coils and the Doppler backscattering method [2] in the frequency range of 100 – 200 kHz. The frequency of the toroidal mode is determined by \( \omega_{TAE} = V_A/2qR \), where \( V_A^2 = B^2/4\pi m_in_i \) is the Alfvén velocity, \( q \) is the safety factor, \( R \) is the major radius, \( B \) is a local value of magnetic field, \( m_i \) and \( n_i \) are the mass and density of particles that resonate with the Alfvén wave [4]. The excitation of TAE is caused by the resonance of the Alfvén wave with fast particles, which in
the Globus-M (M2) tokamak are fast ions born due to the ionization of the neutral beam. Mode propagation follows the predator-prey model: the accumulation of fast ions leads to increasing of TAE mode, which, in turn, causes redistribution and losses of fast ions when mode magnitude grows significantly. Spatial redistribution and losses, in turn, lead to a damping of the mode. Losses of fast particles due to resonance with Alfvén instabilities may cause two core negative phenomena. First, the population of fast ions in plasma could be significantly reduced, thereby reducing the neutron yield. Secondly, the lost fast particle fraction may hit the wall, that may cause significant damage.

An increase in the magnetic field to 0.7 – 0.8 T and the plasma current to 300 – 400 kA [5, 6] allowed us to continue studying the effect of TAE on fast particle confinement [7]. Earlier, such a dependence was obtained [8] for fields of 0.4 and 0.5 T and currents of 180 – 240 kA. The rate of fast particle losses was acquired from the neutral charge-exchange analyzer diagnostics (NPA). An ACORD-24M analyzer [9] was used having the line of sight set in the tangential direction under the same impact parameter as the axis of neutral beam injection. The total losses of fast ions induced by TAE are proportional to the rate of losses obtained from the NPA diagnostic data. The dependence of the value of drops in flux of charge-exchange neutrals with energy close to neutral beam energy (28.5 keV) on eigenmode magnitude has been obtained. The TAE amplitude was acquired from integrated signal of a Mirnov probe, located at the low field side inside the vacuum vessel. In figure 1 in addition to the previously obtained dependences for 0.4 T, 180 kA, and 0.5 T, 240 kA, the dependences of fast particle losses on the TAE magnitude for magnetic field and current values of 0.6 T, 300 kA, and 0.7 T, 330 kA are presented. As it was previously assumed [7, 8], in spite of an increase in the TAE magnitude at higher values of the magnetic field and current leads to moderate losses of fast particles, which is due to their more compact orbits in plasma at large fields and currents. New experiments confirmed the previously acquired dependence in a wider range of plasma parameters. Based on this data, it is possible to make a favorable forecast for a compact neutron source based on a spherical tokamak, where the toroidal field and current values will be even higher.

![Figure 1. The dependence of the value of NPA flux drops on TAE magnitude for various magnetic fields and plasma currents](image)

2. Alfvén cascades
During the experiments with neutral beam injection (28 keV, 0.85 MW) at the current ramp up stage, magnetic field oscillations with increasing frequency varying in the range of 100 – 300 kHz were registered by magnetic probes [10]. These oscillations were identified as Alfvén
cascades (AC) – figure 2. Although cascades are being frequently observed on large tokamaks, for example, JET [11], including spherical ones, such as NSTX [12, 13], they were not previously detected on Globus-M. The reason is that one of the conditions of their excitation is low values of \( \beta_e = \frac{8\pi p_e}{B_0^2} \) \( (p_e \) is electron pressure, \( B_0 \) is the field on the magnetic axis) [12], which could not be achieved during neutral injection at low fields 0.3 – 0.5 T. By increasing the magnetic field to 0.7 – 0.8 T in Globus-M2, the observation of ACs became possible. The detection of Alfvén cascades opened up new diagnostic opportunities, namely, observation of the evolution of \( q_{\text{min}} \) (the minimum value of the safety factor) at the current ramp up stage. At low values of \( \beta_e \), the cascade frequency follows the dispersion relation for the shear Alfvén wave [4, 11] \( \omega^2 = k_\parallel^2 V_A^2 \), where \( k_\parallel = \left( m - nq \right)/qR \) is the wave vector component in the direction of the magnetic field, \( V_A \) is the Alfvén velocity, \( m \) and \( n \) are the poloidal and toroidal wavenumbers, respectively.

At the current ramp up stage, \( q \) decreases proportionally to plasma current, hence the cascade frequency increases up to the TAE frequency \( (\omega_{\text{TAE}} = V_A/2qR) \) and mode transformation does not occur [11]. When neutral injection is turned on at the stage of current ramp up, a favorable situation is formed for AC excitation, since injection causes local increase in the bulk plasma temperature, which may lead to the reversal of the \( q \) profile.

**Figure 2.** First observation of Alfvén cascades on Globus-M2. Shot #37921, 120 – 170 ms.

Alfvén cascade is able to arise only close to the radius of the zero magnetic shear \( r/q \cdot dq/dr \), where it is not affected by damping in Alfvén continuum [4]. Thus, it is possible to calculate time evolution of \( q_{\text{min}} \) analyzing mode frequency acquired from the magnetic probe. At higher \( \beta_e \) values an influence of plasma turbulence become sufficient and it lead to the resonance of Alfvén and geodesic-acoustic (GAM) eigenmodes at low frequencies [14]. The resulting cascade frequency in linear approach is determined by [12]:

\[
\omega_{\text{AC}}^2 = k_\parallel^2 V_A^2 + \frac{c_s^2}{2R^2}
\]

from where one is able to obtain \( q_{\text{min}} \) (the second term is GAM frequency and \( c_s^2 = (T_e + 7/4 \cdot T_i)/m_i \)). Such a method to determine \( q_{\text{min}} \) from AC frequency is called MHD- or magnetic spectroscopy [12, 13] and it is notable for that the only data on magnetic measurements and profiles of electron temperature and density are required to apply this technique. The results of \( q_{\text{min}} \) determination by means of the discussed method are presented in figure 3 (a). For calculation of \( q_{\text{min}} \) we used values of electron density and temperature in the region of minimal \( q \) from the profiles, obtained with Thomson scattering diagnostic (TS) – figure 3 (c). Toroidal wavenumbers \( n \) were determined directly by phase shift of signals of 4 Mirnov coils, located along the toroidal turn, and poloidal wavenumbers \( m \) – by means of the technique, discussed in
paper [12]. For a number of shots we made a comparison of the results, obtained by the MHD-spectroscopy and the numerical calculation of $q_{\text{min}}$ carried out using the ASTRA transport code. The results of modelling for shot #38035 are also presented in figure 3 (a) – stars. In addition, ASTRA modelling showed spatial position of the $q$ reversal radius in central region of plasma close to $\rho = 0.3$ – figure 3 (b).

![Figure 3](image-url)

**Figure 3.** Determination of $q_{\text{min}}$ by means of MHD-spectroscopy. Globus-M2 shot #38035 a) Evolution of $q_{\text{min}}$ (stars – calculation of $q_{\text{min}}$ using ASTRA) 130 – 150 ms. b) Electron temperature profile at 134 ms (solid line – ASTRA, rectangles – TS experimental data). c) Safety factor profile (solid line) and magnetic shear (dashed line) at 134 ms (ASTRA).

Alfvén cascades have also been detected by means of the Doppler backscattering diagnostic (DBS). The possibility of detecting Alfvén modes is due to the fact that the radial component of the electric field of the Alfvén wave causes fluctuations in the $[\mathbf{E} \times \mathbf{B}]$ drift velocity in this field. These velocity oscillations at the frequencies of Alfvén modes were recorded by the DBS method as oscillations of the Doppler shift of backscattered radiation [2, 15]. During a number of experiments where Alfvén cascades were detected, 4 channels of the reflectometer were used, probing the peripheral region of the plasma up to $\rho = 0.7 – 0.6$ depending on the density.

It is noteworthy that on the DBS spectrograms, as well as on the spectrograms obtained from the magnetic probe signal, fragments with increasing frequency are visible, indicating the appearance of Alfvén cascades. With a decrease in the probing frequency, a monotonic decrease
in velocity fluctuations was observed (see figure 4), indicating a decrease in perturbations of the magnetic field with increasing radius [2]. Such a radial dependence does not contradict the assumption of core localization of the instability and modelling that was carried out. To determine the real region of the origin of Alfvén cascades, 6 more channels of the DBS reflectometer with a higher probing frequency will be applied, which installation has recently been successfully completed on the Globus-M2 tokamak.

**Figure 4.** DBS signal spectrogram for 4 reflectometer channels: $\rho = 1.0$, $\rho = 0.9$, $\rho = 0.8$ and $\rho = 0.7$. Shot #38404, 130 – 160 ms.

3. High frequency global modes
Along with other diagnostics, Globus-M2 is improving its magnetic probe system. In particular, the frequency range of signal recording for four toroidal probes was expanded. At the moment, the sampling frequency of the magnetic probe signal is 10 MHz, and the bandwidth is 50 kHz – 3 MHz.

**Figure 5.** Shot #38661 Mirnov coil signal spectrogram 160 – 200 ms. Soft X-ray detector signal is overlaid over the spectrogram. Yellow rectangle corresponds to LH heating pulse.
Due to this, high-frequency oscillations (about 1 MHz) were detected both in LHCD experiments and in ohmic discharges that had not previously been registered on the Globus-M (M2) tokamak – figure 5. The bursts registered in ohmic discharges generally have lower magnitudes measured than it is for discharges with LH heating. The detected signals represent themselves as magnetic field oscillation bursts with their duration of about 100 $\mu$s and a period of 1 – 2 ms. Time moments of the excitation of the bursts are correlated with moments of sawtooth disruptions – figure 5. Highly likely the explanation of the origination of detected oscillations is that global Alfvén eigenmode is driven by a beam of runaway electrons [16, 17].

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