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THE STUDY OF ALFVÉN EIGENMODES ON THE SPHERICAL TOKAMAK GLOBUS-M2 USING DOPPLER BACKSCATTERING

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Abstract

Alfven eigenmodes (AEs) are a topic of research on the spherical tokamak Globus-M2 (minor radius a = 0.24 m, major radius R = 0.36 m, R/a = 1.5) which was designed to reach toroidal magnetic fields up to 1 T and plasma current 0.5 MA. In experiments with neutral beam injection (NBI) several types of AEs have been observed: Alfven cascades (AC) are detected during current ramp up, chirping toroidal Alfven eigenmodes (TAE) and Doppler shifted TAE (DS TAE) can be seen at a later stage of auxiliary heating. It has been demonstrated on Globus-M that the microwave diagnostic DBS can be used to detect the drift velocity fluctuations in crossed radial electric field of the Alfven wave and tokamak magnetic field, however the DBS system available at the time did not allow to obtain comprehensive measurements. On Globus-M2 the installed multi-frequency DBS systems cover an interval of normalized minor radii ρ = 0.6–1.1 for typical Globus-M2 discharges, allowing to determine the localization of the various AEs. The results demonstrate that the TAE exists at radii 0.45-0.55 m and disappears in the plasma core. DS TAE were detected in a similar range of radii 0.45–0.55 m. ACs were seen to develop in slighter deeper regions at radii 0.45–0.51 m. The dependence of the AE localization on plasma parameters such as magnetic field, plasma current and electron density was also investigated. The turbulence level and average poloidal rotation velocity were seen to exhibit changes during AEs.

1. INTRODUCTION

Electromagnetic waves propagating along the magnetic field B with wavenumber $k_\parallel$ and frequency $\omega = k_\parallel V_A$ (where $V_A = B/\sqrt{(4\pi\rho)}$ is the Alfvén velocity with ρ being the mass density of the plasma) are known as Alfvén waves [1]. Various types of Alfvén eigenmodes (AEs) can be driven unstable by energetic particles when the resonance condition is satisfied and are commonly observed in laboratory plasmas. In a toroidal plasma, these modes lead to the ejection the high-energy particles from the plasma [2] which in turn can cause significant loss of beam power (with degradation of plasma performance) and damage to the plasma facing components. Thus, understanding the physics and mechanisms of the AEs is important from both a fundamental scientific perspective and for the practical realization of fusion energy.

AEs have been a topic of research on the spherical tokamak Globus-M and now its modernised version Globus-M2 (minor radius a = 0.24 m, major radius R = 0.36 m, R/a = 1.5) [3] which was designed to reach toroidal magnetic fields B_T up to 1 T and plasma current I_p up to 0.5 MA. The increase of plasma parameters and upgrade of the neutral beam injection (NBI) system [4] led to better fast particle confinement and changed the nature of the observed AEs with an expansion of their frequency spectrum. On Globus-M2, along with chirping toroidal Alfvén eigenmodes (TAE) previously observed on Globus-M, Alfvén cascades (AC or reversed shear AE (RSAE)), Doppler shifted TAE and energetic particle modes (EPMs) were identified. Studies of AEs have been carried out using arrays of magnetic probes which allowed to determine their mode structure and amplitude [5, 6]. TAE-induced losses of fast particles have been investigated using a neutron spectrometer and ACORD-24M neutral particle analyser (NPA) [7, 8].

It had also been demonstrated on Globus-M that the Doppler backscattering (DBS) diagnostics can be used to detect AEs (TAE in the case of Globus-M) [9,10], however the DBS system available at that time did not allow to obtain comprehensive measurements. This work presents the results of the AE study using DBS on Globus-M2 in a wide range of plasma parameters: I_p = 160-450 kA, B_T = 0.5-0.95 T, $n_e = 10^{19}$-10^{20} m^{-3}, E_{NBI} = 20-50 keV, P_{NBI} = 0.3-1.5 MW.

2. DOPPLER BACKSCATTERING FOR THE STUDY OF ALFVEN EIGENMODES

The microwave diagnostic Doppler backscattering (DBS, or Doppler reflectometry) is based on the detection of backscattered radiation near the cutoff of the probing microwave beam [11]. The scattering takes place off density fluctuations with a selected wave vector $k_\perp$ which satisfies the Bragg's law of $k_\perp = 2k_i$ with k_i being the wavevector of the incident wave. A Doppler frequency shift $\Delta\omega_D$ is induced when the fluctuating plasma experiences movement in the direction of either the electron or ion diamagnetic drift at a velocity of $V_\perp$ which can be determined using the formula $V_\perp = \Delta\omega_D/k_\perp$. The velocity $V_\perp$ can be described as the sum of two components: the phase velocity of the density fluctuations V_{phase} and the E×B drift velocity $V_{E\times B}$. DBS has become an integral part of plasma research on most magnetic confinement devices. The main role of the diagnostic is to provide nonperturbative characterization of turbulent density fluctuations and flows with non-invasive local measurements of parameters such as the k-spectrum and profile of rotation velocity of the plasma fluctuations. The field of application of the DBS method has expanded including measurements of low and intermediate-$k_\perp$ fluctuations, radial correlation lengths, and coherent magnetohydrodynamic (MHD) mode studies [12-15].

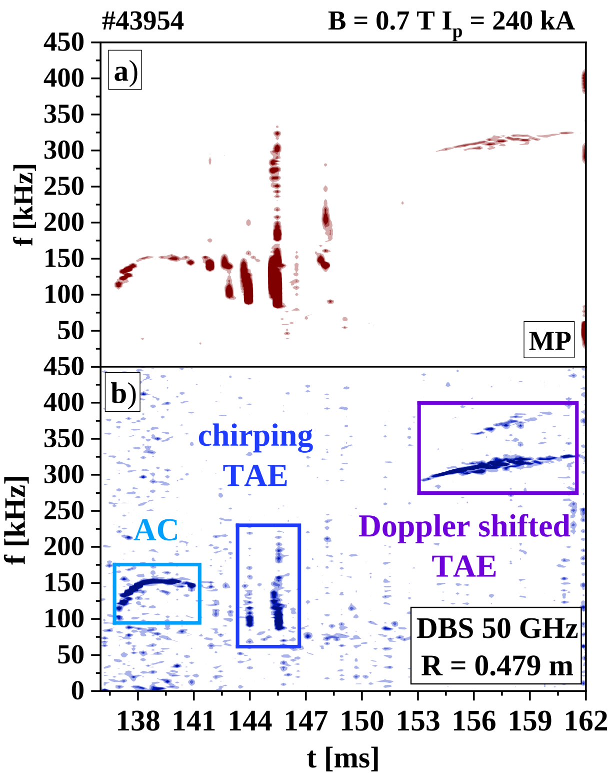

Figure 1. Spectrograms of the a) magnetic probe signal, b) Doppler frequency shift for discharge #43954. AEs such as ACs, TAE and DS TAE can be observed both in the MP and DBS signals.

During the course of research using the DBS method, oscillations at AE frequencies were detected in the Doppler frequency shift signals (corresponding to the plasma rotation velocity $V_\perp$) [16]. These oscillations are observed simultaneously with bursts in the magnetic probe (MP) signal, as demonstrated in Figure 1. The possibility of detecting AEs using DBS is due to the fact that the radial component of the electric field of the Alfvén wave causes fluctuations in the E×B drift velocity $V_{E\times B}$ in this field.

The DBS systems on Globus-M2 are installed on the low-field side (LFS) [17,18]. In total, 3 diagnostic ports are currently used by the available DBS systems: the 1st is located in the equatorial plane, the 2nd 14 cm above it and the 3rd 14 cm below it. The first DBS system with 4 fixed probing frequencies 20, 29, 39, 48 GHz was carried over from the previous Globus-M. It covers an interval of normalized minor radii ρ = 0.8–1.1 for the discussed Globus-M2 discharges. The second DBS system 6 fixed probing frequencies 50, 55, 60, 65, 70, 75 GHz expands the detection region to ρ = 0.2–0.8. The possible positions of the DBS systems and the trajectories of the probing beams are presented in Figure 2a, b) on the poloidal cross-section of the Globus-M2 tokamak. Ray tracing of the probing beam trajectories is performed to obtain wavevector and cut-off radii values [19]. In the analyzed experiments the plasma was probed in O-mode. The radial resolution of the diagnostic is 0.5 cm.

3. TOROIDAL ALFVEN EIGENMODES

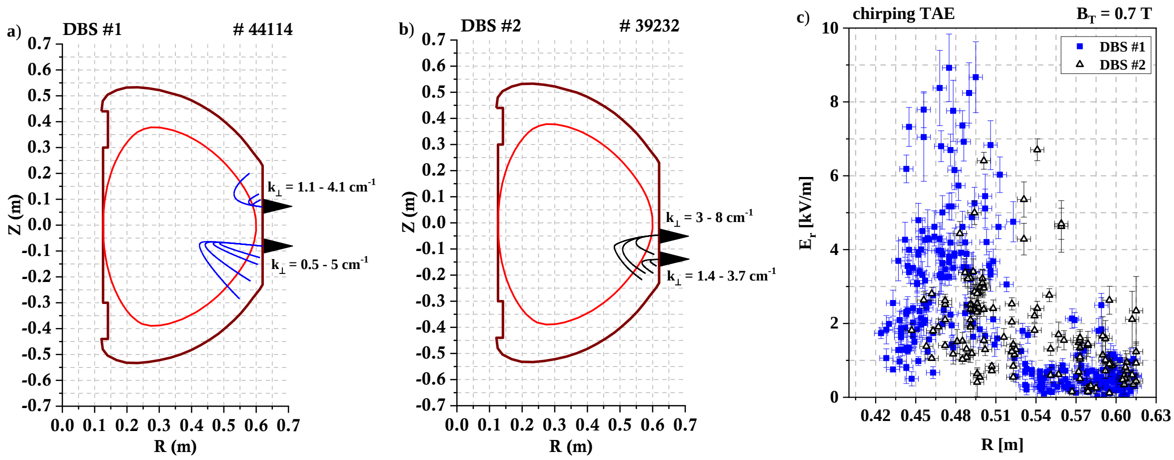

Figure 2. a) ray tracing for DBS setup #1, b) ray tracing for DBS setup #2, c) radial profiles of TAE E_r amplitudes. Despite different DBS geometry, the obtained E_r values are relatively similar (the observed differences can be attributed to differences in compared discharges).

The aim of the first experiments using the upgraded multi-frequency DBS on Globus-M2 was to investigate how far the TAE previously observed on Globus-M extend inside the discharge [20]. Conditions of Globus-M discharges were reproduced and the results allowed to demonstrate the decay of the TAE oscillations in the central plasma regions. An example of such observations can be seen in Figure 2c where it can be seen the TAE E_r amplitudes decrease significantly at R = 0.43 for the blue profiles and at R = 0.46 m for the black ones.

As DBS is sensitive to the wave vector $k_\perp$ of the density fluctuations off which the scattering takes place, experiments were conducted with different DBS geometries to investigate the effect on the observation of AEs. The compared DBS set-ups with the corresponding $k_\perp$ values are shown in Figure 2a (DBS#1, shown in blue) and 2b (DBS#2, shown in black). In the case of DBS#1 $k_\perp$ ranged from 0.5 to 4.1 cm^{-1}, while for DBS#2 $k_\perp$ range was wider and had higher values from 1.4 to 8 cm^{-1}. Radial profiles of TAE E_r amplitudes were obtained for both cases and are presented in Figure 2c. The results indicate that, despite different DBS geometries, the TAE E_r amplitudes are of the same order with DBS#1 profiles ranging from 0.5 kV/m to 9 kV/m and DBS#2 from 0.5 to 7 kV/m. Unfortunately, the compared discharges were not entirely identical: despite similar plasma parameters, different NBI sources were used (see NBI-1 (used in DBS#2 case) and NBI-2 (used in DBS#1 case) in [4]), which contributes to differences both in values and area of development of the TAE.

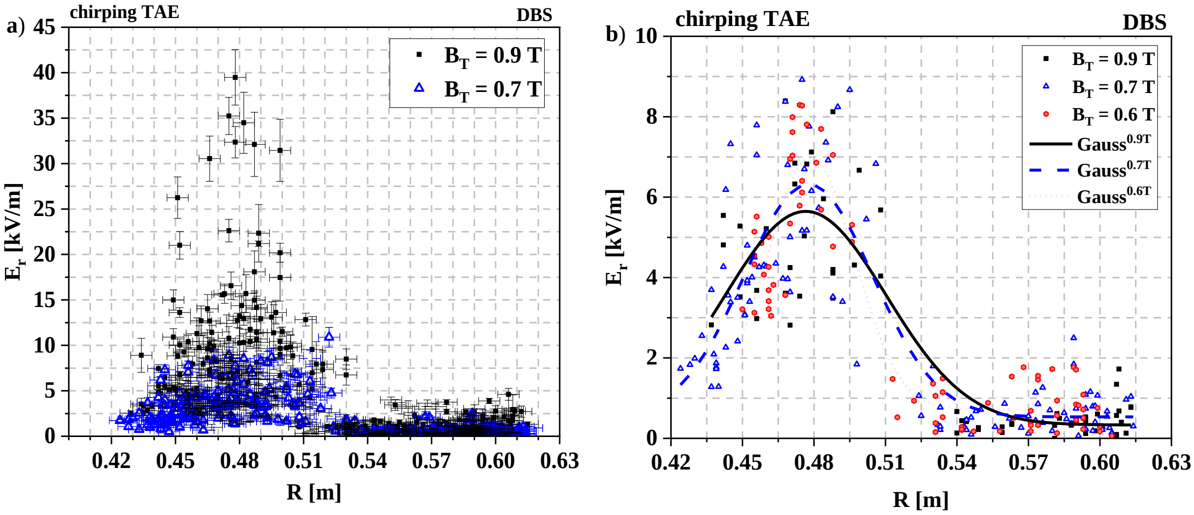

Figure 3. a) radial profiles of TAE E_r amplitudes for 0.9 T (black squares) and 0.7 T (blue triangles), b) radial profiles of TAE E_r amplitudes for 0.9 T (black squares), 0.7 T (blue triangles), 0.6 T (red circles) with corresponding Gaussian fits. The increase of the magnetic field leads to an increase of the TAE E_r amplitude and to a widening of the profile.

The effect of the increase of plasma parameters on profiles of TAE E_r amplitudes was also investigated. A multitude of profiles were calculated for different B_T with the results being shown in Figure 3a (radial profiles of TAE E_r amplitudes for 0.9 T are represented by black squares and for 0.7 T by blue triangles). It was observed that the increase of the magnetic field B_T leads to the increase of the range of measured E_r amplitudes: in the case of B_T = 0.7 T the E_r amplitudes reached a maximum of 10 kV/m, while for B_T = 0.9 T the E_r amplitudes reach up to 40 kV/m, as demonstrated in Figure 3a. When comparing profiles with similar E_r amplitude values, but varying plasma parameters (B_T from 0.6T to 0.9T), it was noted that the higher the B_T, the wider the profile around the local maximum of R = 0.48 m (see Gaussian fits in Figure 3b). Additionally, it was noted that in the case of lower B_T there is an increase of TAE E_r amplitudes at the edge at R = 0.55 – 0.62 m: for 0.9 the E_r is about 0.5 kV/m, but for 0.6 T it reaches values up to 2 kV/m. This is in line with measurements of 3-4 kV/m at similar radii for discharges with even lower B_T = 0.5 T on Globus-M.

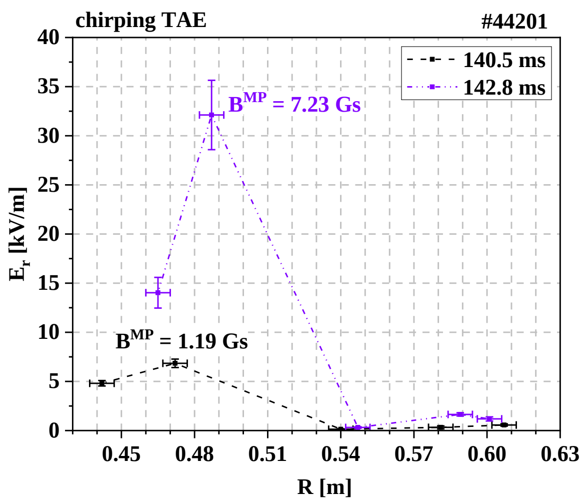

Figure 4. Radial profiles of TAE E_r amplitudes for discharge #44201. The increase in TAE E_r amplitude measured by DBS coincides with MP measurements.

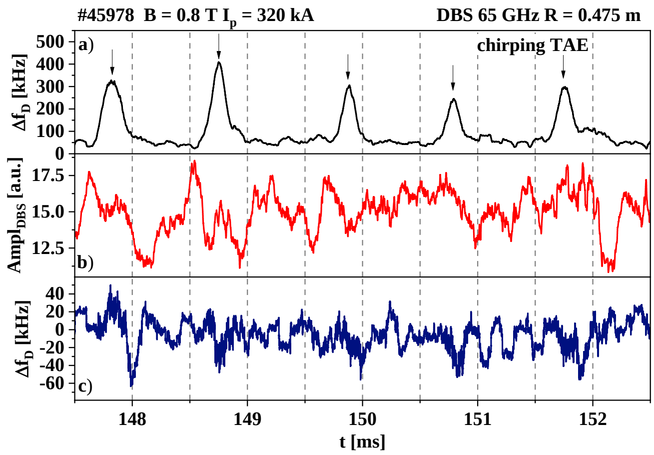

Figure 5. a) TAE amplitude, b) amplitude of complex DBS signal, c) Doppler frequency shift Δf_D for discharge #45978. The turbulence level and average poloidal rotation velocity exhibit changes during TAE.

DBS measurements were compared with MP measurements of the TAE magnetic field amplitude B^{MP}. Results demonstrate that higher B^{MP} values correlate to higher E_r amplitudes, as shown in Figure 4. The B^{MP} of the presented TAE bursts differ by a factor of 6, as do the maximum E_r. If we assume that oscillations in the Doppler shift are due to the drift velocity in the radial electric field of the Alfvén wave, then using this assumption, we can calculate the amplitude of oscillations of the poloidal magnetic field projection for the Alfvén electromagnetic wave by the formula $B_\theta = \frac{nE_r}{Rw}$, where n is the toroidal mode number and w is the TAE frequency. In the experiment, TAE frequencies were observed in the range from 100 to 250 kHz (depending on plasma parameters). Using magnetic probes, the poloidal and toroidal mode numbers m and n were determined: as a rule, the n = 1, m = 2, 3 modes are observed. For the presented case, it is estimated that the maximum B_θ measured using DBS is 33.5 Gs and 182.9 Gs. These values are much greater than those measured by MPs which might be explained by the fact that DBS provides local measurements in this region.

The turbulence level and average poloidal rotation velocity (and the corresponding radial electric field) exhibit changes during AEs. For example, in the case of chirping TAE (see Figure 5), it can be seen that there is a decrease in turbulence amplitude (represented by amplitude of complex DBS signal $\mathrm{Ampl}_{\mathrm{DBS}}$) and velocity (represented by the Doppler frequency shift Δf_D) associated with each burst.

4. ALFVEN CASCADES

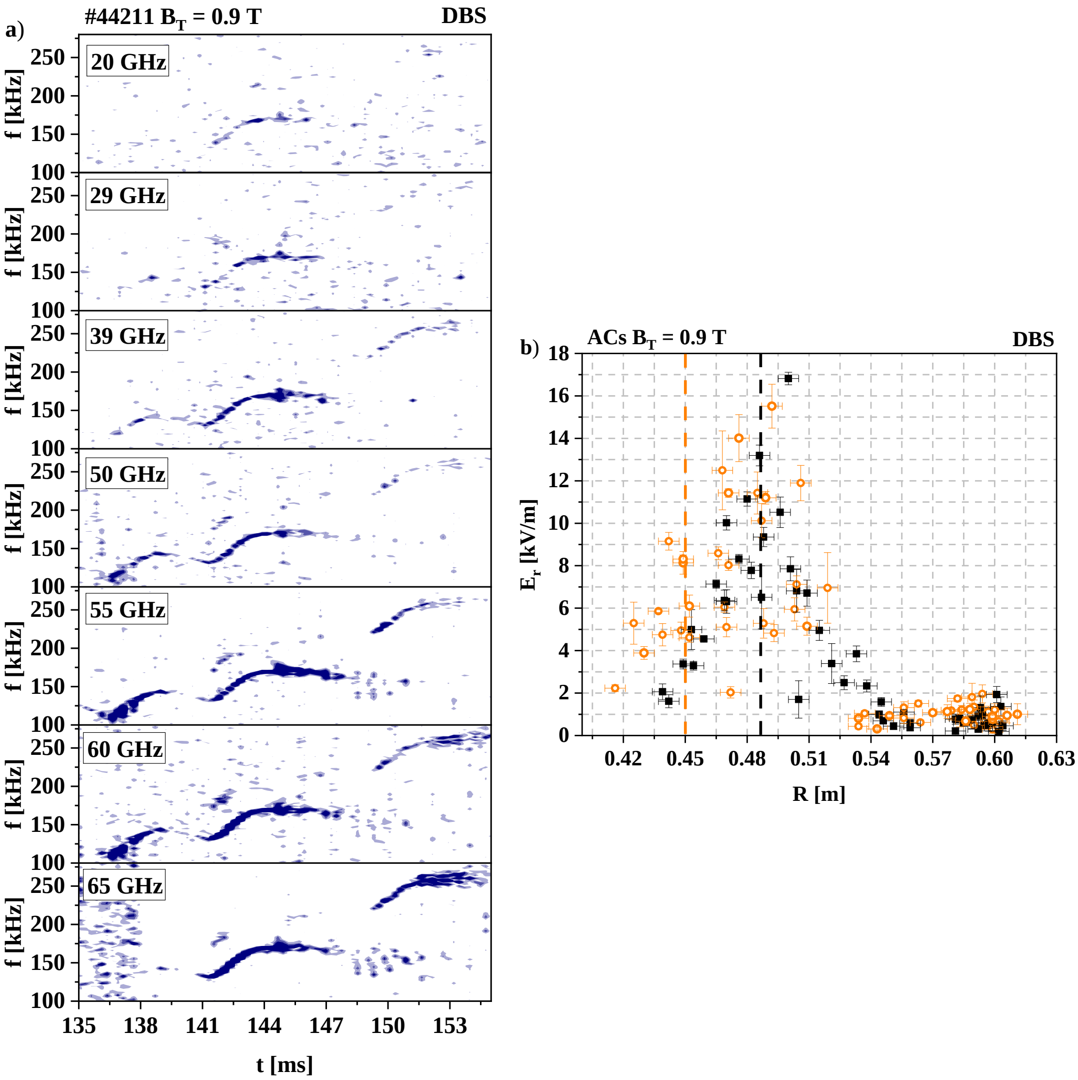

Figure 6. a) spectrograms of 20, 29, 39, 50, 55, 60, 65 GHz DBS channels demonstrating AC detection, b) radial profiles of AC E_r amplitudes (black squares – narrowly localised AC profiles, orange circles – wider and deeper AC profiles).

At the current ramp up stage of discharges when a reversed shear of the magnetic field may appear in the plasma, magnetic field oscillations with increasing frequency varying in the range of 100 – 300 kHz were detected. These oscillations were identified as ACs. A series of ACs can be seen on different DBS channels in Figure 6a. Their appearance was explained by a decrease in parameter $\beta_e = 8\pi p_e/B_T$ (p_e is the gas kinetic pressure of electrons) due to the increase of the magnetic field on Globus-M2 [5]. Multi-frequency DBS was used to determine the AC localization, the resulting radial profiles of AC E_r amplitudes are presented in Figure 6b. Overall, AC were detected in the range of radii R = 0.41- 0.54 m with E_r amplitudes from 1 to 17 kV/m. Several types of AC profiles can be observed: black squares represent narrowly localised AC profiles with a local maximum at about R = 0.48 m, while orange circles show deeper AC profiles which seem to span even further into the plasma (however, in some cases the available probing frequencies do not allow to construct a full profile). Such oscillations develop in the region of the minimum of safety factor q_{min}, i.e. in the more central regions of the discharge, so the differences in AC profiles seem to stem from differences in the safety factor profiles (there is an approximately 30% difference between safety factor values at the axis between the discharges). The DBS data regarding the region of AC localization makes it possible to estimate the radius with q_{min} and compare it with the calculations obtained using the ASTRA code [5].

5. DOPPLER SHIFTED TAE

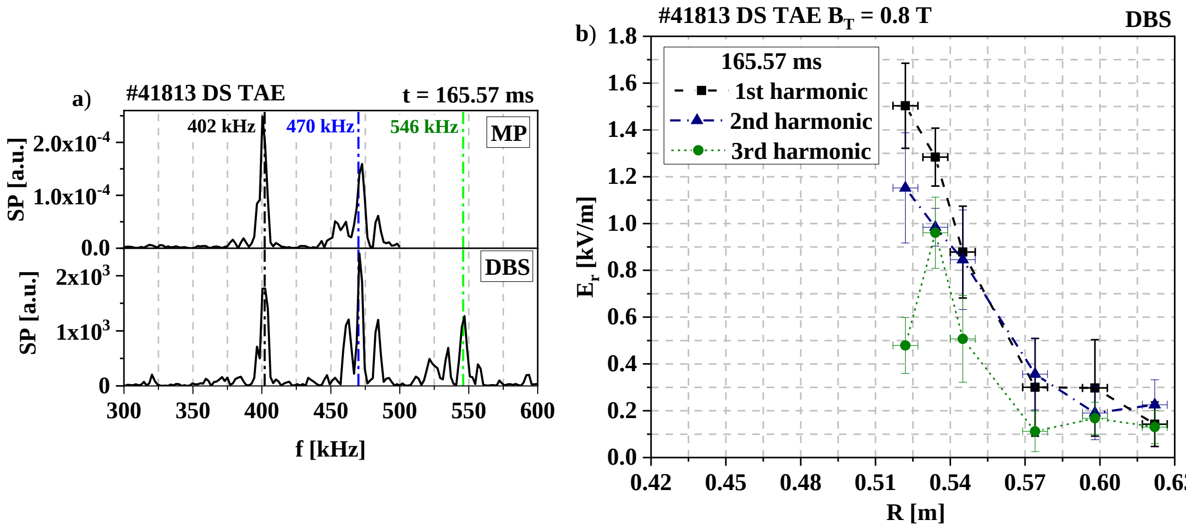

Figure 7. a) Spectra of magnetic probe and Doppler frequency shift signals for discharge 41813 (DS TAE harmonics clearly seen), b) radial profiles of DS TAE E_r amplitudes for different harmonics.

After the increase of the main plasma parameters and an improvement of fast particle confinement on Globus-M2, long AE oscillations existing for 1-5 ms with a quasi-stationary frequency in the 250-600 kHz range could be observed during a late stage of NBI heating. The analysis of the frequency components using MPs and DBS showed that the toroidal number of the modes was n = 1,2,3. As the frequency could be described by the formula $f = f_{TAE} + n \cdot f_{Doppler}$, where f_{TAE} is the frequency of first TAE harmonic in the absence of plasma rotation and $f_{Doppler}$ is the Doppler shift of the observed frequency, these AE were understood to be Doppler shifted TAE (see Figure 1). Generally, the DBS diagnostics was able to observe the mode in the region of radii 0.45– 0.57 m. An example of the radial profiles for discharge #41813 is presented in figure 7b. In this case several harmonics were observed: DBS was able to detect 3 harmonics as shown in Figure 7a. The first two harmonics extend deeper into the plasma detected using DBS at R = 0.52-0.57 m), while the 3rd has a local maximum at around 0.53 m. These results are similar to observations on Globus-M where higher TAE harmonics developed closer to the separatrix [19]. DBS and charge exchange recombination spectroscopy (CXRS) measurements indicate that the DS TAE location coincides with the region of the maximum gradient of the toroidal rotation velocity [6].

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REFERENCES

[1] HEIDBRINK W. W. Phys. Plasmas **15** (2008) 055501 https://doi.org/10.1063/1.2838239

[2] GARCÍA-MUÑOZ M. et al Nucl. Fusion **50** (2010) 084004 https://doi.org/10.1088/0029-5515/50/8/084004

[3] PETROV YU.V. et al Nucl. Fusion **62** (2022) 042009 https://doi.org/10.1088/1741-4326/ac27c7

[4] SHCHEGOLEV P.B. et al. Plasma Phys. Rep. **49** (2023) 1501–1514 https://doi.org/10.1134/S1063780X23601098

[5] BALACHENKOV I.M. et al Tech. Phys. Lett. **46** (2020) 1157–1161 https://doi.org/10.1134/S1063785020120032

[6] BALACHENKOV I.M. et al Plasma Phys. Rep. **50** (2024) 765–772 https://doi.org/10.1134/S1063780X24600713

[7] BAKHAREV N. N. et al Phys. Plasmas **30** (2023) 072507 https://doi.org/10.1063/5.0156337

[8] SKREKEL O.M., et al. "Study of fast ion transport and losses during Alfvén type MHD instabilities at Globus-M2" 30th IAEA Fusion Energy Conference (Chengdu, People's Republic of China, 2025).

[9] BULANIN V.V. et al Tech. Phys. Lett. **43** (2017) 1067–1070 https://doi.org/10.1134/S1063785017120033

[10] BULANIN V.V. et al Tech. Phys. Lett. **45** (2019) 1107–1110 https://doi.org/10.1134/S1063785019110051

[11] CONWAY G.D. et al Plasma Phys. Control. Fusion **46** (2004) 951 https://doi.org/10.1088/0741-3335/46/6/003

[12] ESTRADA T. et al Nucl. Fusion **52** (2012) 082002 https://doi.org/10.1088/0029-5515/52/8/082002

[13] YASHIN A. et al Appl. Sci. 13 (2023) 3430. https://doi.org/10.3390/app13063430

[14] PONOMARENKO A. et al Nucl. Fusion **64** (2024) 022001

[15] YASHIN A. Y. et al "First results of EHO-like fluctuations studies at the spherical tokamak Globus-M2" 30th IAEA Fusion Energy Conference (Chengdu, People's Republic of China, 2025)

[16] BULANIN V.V. et al Phys. Atom. Nuclei **83** (2020) 1124–1130 https://doi.org/10.1134/S1063778820070042

[17] YASHIN A.Y. et al JINST **17** (2022) C01023 https://doi.org/10.1088/1748-0221/17/01/C01023

[18] BULANIN V. V. et al Rev. Sci. Instrum. **92** (2021) 033539 https://doi.org/10.1063/5.0030307

[19] YASHIN A.Y. et al JINST **10** (2015) P10023 https://doi.org/10.1088/1748-0221/10/10/P10023

[20] BULANIN V.V. et al Tech. Phys. Lett. **47** (2021) 197–200 https://doi.org/10.1134/S1063785021020206