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FIRST RESULTS OF EHO-LIKE FLUCTUATIONS STUDIES AT THE SPHERICAL TOKAMAK GLOBUS-M2

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Abstract

In experiments with neutral beam injection heating on Globus-M2 EHO-like oscillations have primarily been observed in weakly shaped discharges with triangularity values $\delta < 0.2$ and large safety factor $q_{95} \leq 6$. They were detected in the form of harmonics of coherent fluctuations on various diagnostics, such as the D_α emission light, magnetic and Langmuir probes, interferometry and Doppler backscattering (DBS). Measurements confirming EHO development at the plasma edge. The poloidal mode numbers of the EHO were found to be a superposition of m = 1 and 3. The pedestal conditions during the EHO phase of the Globus-M2 discharge were close to the peeling-ballooning stability limit in the linear 3-field MHD simulations that used the BOUT++ code. The most unstable mode had low toroidal numbers (n=5). During the EHO-like oscillations there is an apparent slowing down of the increase of the average electron density and electron temperature measured using Thomson scattering diagnostics. However, the ion temperature obtained using charge exchange recombination spectroscopy (CXRS) seems to increase more rapidly after the start of the EHO. A steady decrease of the effective ion charge with its gradual increase after the mode's disappearance indicates changes in the impurity content in this regime. CXRS was also able to detect an increase on the toroidal rotation velocity as well as the toroidal rotational shear. The perpendicular rotation velocity at the plasma edge measured using DBS changes dramatically after the start of the EHO-like oscillations going from negative to positive. Multi-frequency DBS allowed to investigate the changes in profiles velocity and the corresponding radial electric field.

1. INTRODUCTION

The high confinement mode (H-mode), while being the most favorable operational regime for future fusion devices [1], is often limited by the formation of edge localized modes (ELMs) [2]. They cause the expulsion of particles and energy to the plasma edge, thus degrading plasma performance. ELMs produce high heat loads on the plasma facing components on short time scales and can ultimately damage the physical state of the device. On the other hand, ELMs also play a role in the removal of impurities and control of the plasma density. These seemingly contradicting effects to the plasma performance make the phenomenon a subject of great interest and intense research, as the underlying physics remains elusive. The importance of ELM research lies primarily in the ability to mitigate or suppress their activity, therefore, achieving small or no ELM operational regimes [3] may be of significant benefit to the steady-state operation of future fusion reactors.

One potential solution to the ELMy H-mode is the quiescent H-mode (QH-mode) which is an alternative naturally ELM-free regime of improved confinement. Such regimes are specific and have been realized only at a few devices, originally discovered at DIII-D [4] and later also observed on ASDEX Upgrade with a carbon (C) wall [5], JET-C [6] and JT-60U [7]. It is accompanied by the development coherent, narrow electromagnetic modes. They have been referred to as edge harmonic oscillations (EHO) as they lead to a decrease in the density gradient at the periphery not allowing the development of ELMs [8]. EHOs lead to an increase in transport at the edge of the plasma and stabilize the pedestal region [9-11]. The mode typically exhibits low toroidal mode numbers and multiple harmonics. They are thought to be a saturated kink-peeling mode, driven unstable by large edge current densities [12]. EHO-like oscillations have been recently observed on the compact spherical tokamak Globus-M2 and are the subject of the current manuscript.

2. EXPERIMENTAL SETUP

EHO-like oscillations were studied on the compact spherical Globus-M2 tokamak [13-15], which is an upgraded version of the Globus-M, designed to enhance research into compact fusion reactors. The Globus-M2 tokamak (minor radius 0.24, major radius 0.36 m, aspect ratio 1.5) was designed to reach the toroidal magnetic field B as high as 1 T and the plasma current I_p 0.5 MA. The magnetic system provides operation in diverter single or double null configuration with the plasma shape of triangularity δ up to 0.5 and elongation κ up to 2.2. Currently 90% of highest magnetic field and plasma current value have been reached, so during the reported period the experiments were performed with the toroidal magnetic field up to 0.9 T and plasma current up to 0.45 MA.

Globus-M2 is equipped with a rather large neutral beam injector (NBI) heating system [16] and diagnostics complex [17]. EHO were studied using a multi-diagnostic approach which included the Thomson scattering (TS) diagnostics, D_α sensor, magnetic probes (MPs), microwave interferometer, movable Langmuir probe (LP), diagnostics of effective plasma charge, multi-frequency Doppler backscattering (DBS) and diagnostics of charge exchange recombination spectroscopy (CXRS).

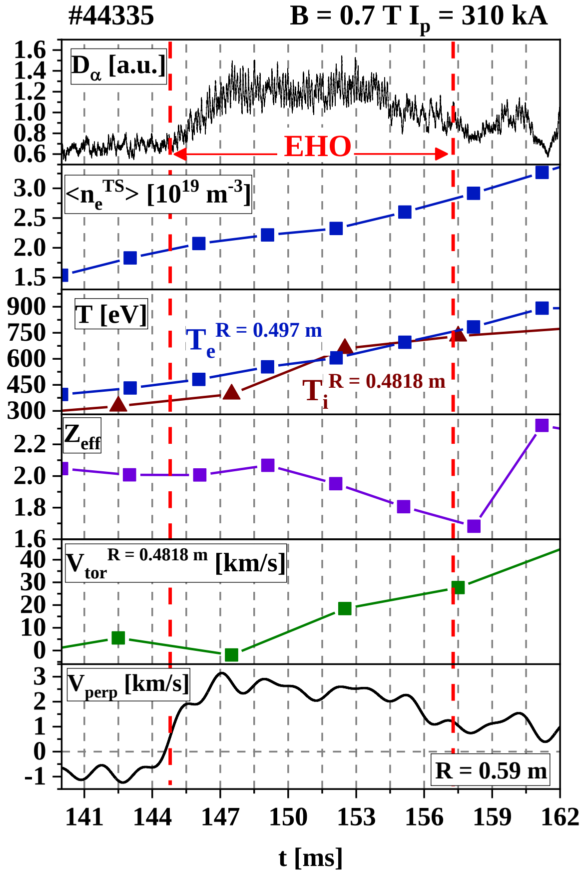

Figure 1. temporal evolution of (from top to bottom) D_α signal, average electron density measured using TS diagnostics $< n_e^{TS} >$, ion T_i (measured using CXRS) and electron T_e (measured using TS) temperatures, effective ion charge Z_{eff}, toroidal rotation velocity V_{tor} and V_{perp}. The start and end of the EHO-like oscillations is indicated by vertical red lines.

EHO-like oscillations have primarily been observed in weakly shaped discharges with triangularity values $\delta < 0.2$ and large safety factor $q_{95} \leq 6$. The dynamics of the plasma parameters during the EHO was also investigated with their temporal evolution presented in Fig.1. During the time of its existence (see EHO-like oscillations indicated by vertical red lines) there is an increase of the D_α light intensity. The average electron density $< n_e^{TS} >$ and electron temperature T_e measured using TS diagnostics also increases, however the rate of this growth seems to slow down. These observations seem to indicate a change in the edge diffusion coefficients. The ion temperature T_i obtained using CXRS at R = 0.4818 m seems to grow more rapidly after the start of the EHO. There is also a steady decrease of the effective ion charge Z_{eff} from 2 to 1.6 with its gradual increase right after the mode's disappearance at 157.8 ms. This serves as an indicator of changes in the impurity content during the EHO. CXRS was also able to detect an increase on the toroidal rotation velocity V_{tor} at R = 0.4818 m. The perpendicular rotation velocity V_{perp} measured using DBS at R = 0.59 cm changes dramatically after the start of the EHO-like oscillations going from negative with values of about 1.5 km/s to positive reaching up to 3 km/s. Multi-frequency DBS allowed to investigate the changes in profiles of the V_{perp} and the corresponding radial electric field.

3. EXPERIMENTAL RESULTS

3.1. EHO-like oscillations on Globus-M2

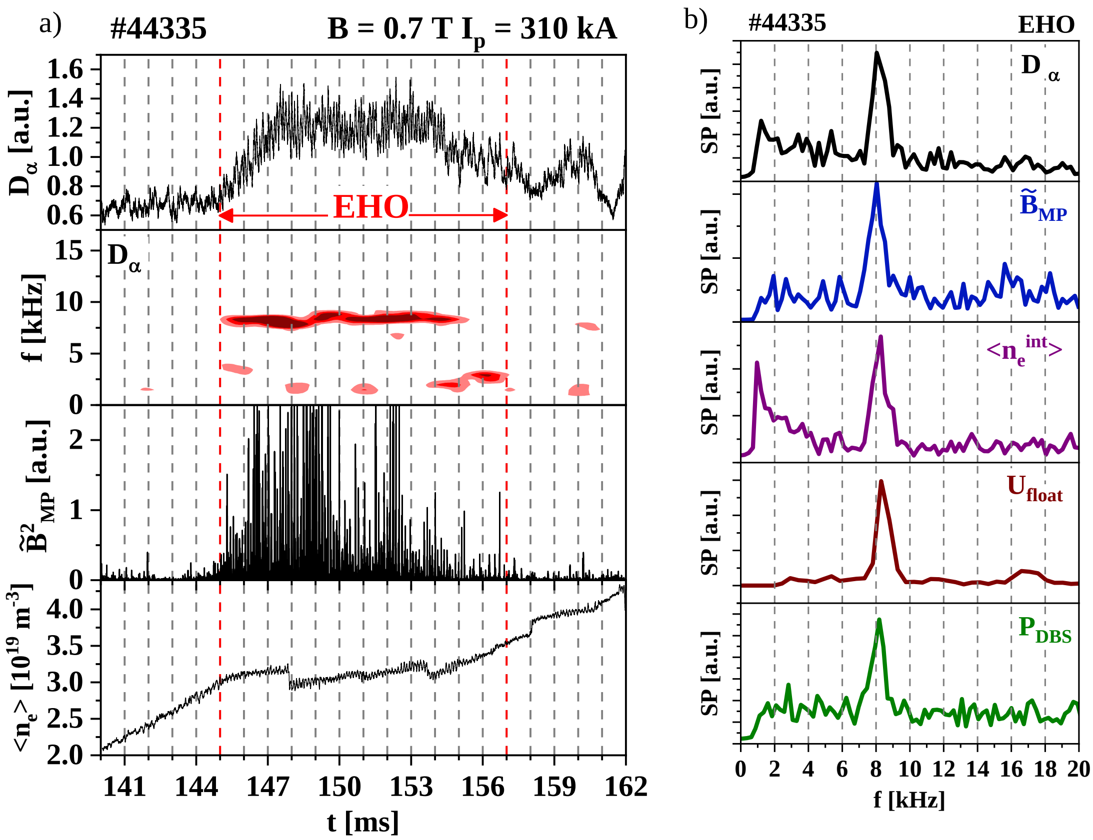

Figure 2. a)(from top to bottom) D_α signal, spectrogram of the D_α light intensity, fluctuations of MP signals amplitude $\tilde{B}_{MP}$, average electron density measured using interferometry n_e^{int}, b) spectra of diagnostics signals (from top to bottom) D_α signal, fluctuations of MP signals amplitude $\tilde{B}_{MP}$, average electron density measured using interferometry n_e^{int}, floating potential U_{float} and DBS backscattered power P_{DBS} at R = 0.59 m exhibit peaks at 8 kHz.

Low frequency EHO-like oscillations (from 5 to 20 kHz) were initially observed on the D_α light intensity (note the specific increase and accompanying oscillations in Figure 2a. A clear low frequency mode can be seen in the spectrogram of the D_α light intensity. It was also observed using a variety of other diagnostics: MPs (in the form of broadband activity), interferometer, Langmuir probe, DBS in both turbulence amplitude and perpendicular rotation velocity signals. This is demonstrated in the spectra of the diagnostics signals in Figure 2b.

3.2. Mode structure

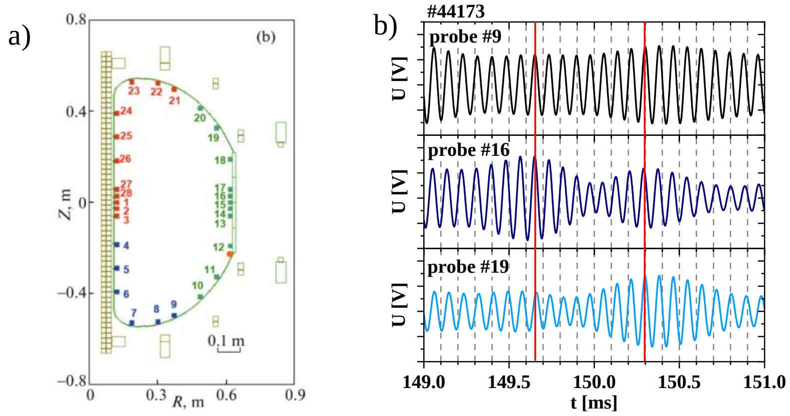

Figure 3. a) array of 28 poloidal magnetic probes on Globus-M2, b) magnetic probe signals.

The array of 28 poloidal magnetic probes [17] (see Figure 3) on Globus-M2 was used to study the mode structure of the EHO. Oscillations at the EHO frequency were systematically observed on all MPs corresponding to a full range of poloidal angles as demonstrated in Figure 3b. However, a time shift between the maxima can be observed which indicates a complex structure of the magnetic field fluctuations associated with the EHO development. To obtain information on the spatial distribution of the oscillations studied, the cross-phase between pairs of all available signals of the poloidal MPs array was constructed. Analysis showed that the poloidal mode numbers of the EHO seem to be a superposition of m = 1 and 3. The analysis of the toroidal mode numbers was more challenging and is a subject of future research.

3.3. EHO radial profile

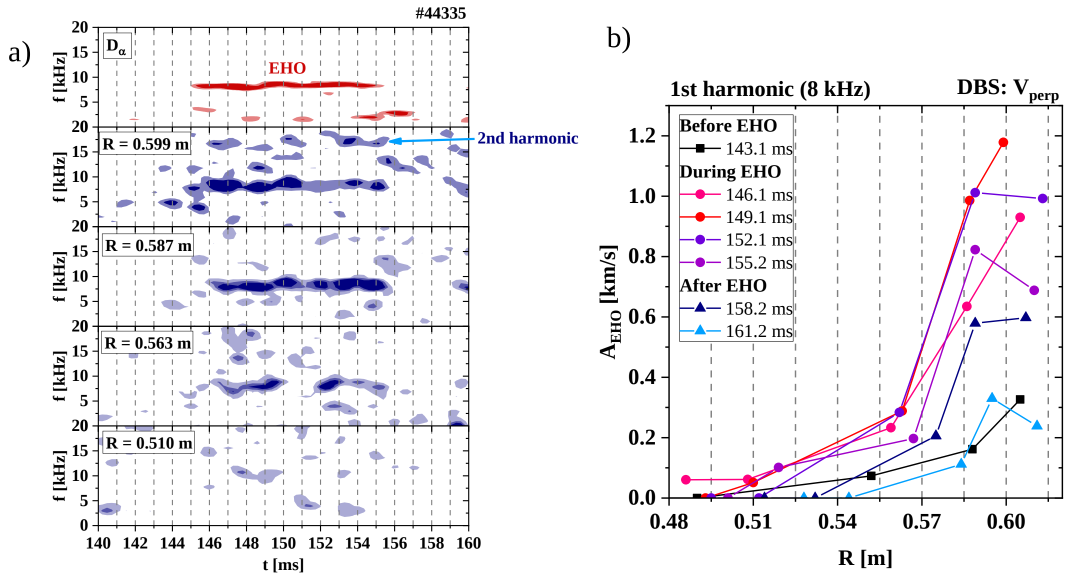

Figure 4. a) spectrogram of the D_α and DBS velocity V_{perp} signals, b) radial profile of EHO velocity amplitudes A_{EHO}

Multi-frequency DBS [18, 19] is available on Globus-M2 and allows to investigate the radial dependence of plasma parameters or studied phenomena. This is why it was possible to determine the area of EHO development. Analysis showed that not every channel was able to detect the EHO. This is demonstrated in Figure 4a where spectrograms of several DBS channels are shown. In the shown example (estimated using perpendicular velocity V_{perp} measurements) the EHO developed at radii R = 0.56-0.61 m. This means that, generally, the EHO develop at the plasma edge, close to the separatrix (these observations are also confirmed by LP measurements). Figure 4b shows their velocity amplitudes A_{EHO}: it can be seen that during the EHO the amplitude reaches values up to 1.2 km/s. Before (at 143 ms) and after (after 156 ms) the EHO the velocity amplitudes A_{EHO} drop by more than two-fold and are at values not above the background turbulence.

Additionally, several harmonics of the EHO can be seen (see Figure 4a) and their localization differs from the main one.

3.4. Dynamics and distributions of plasma parameters

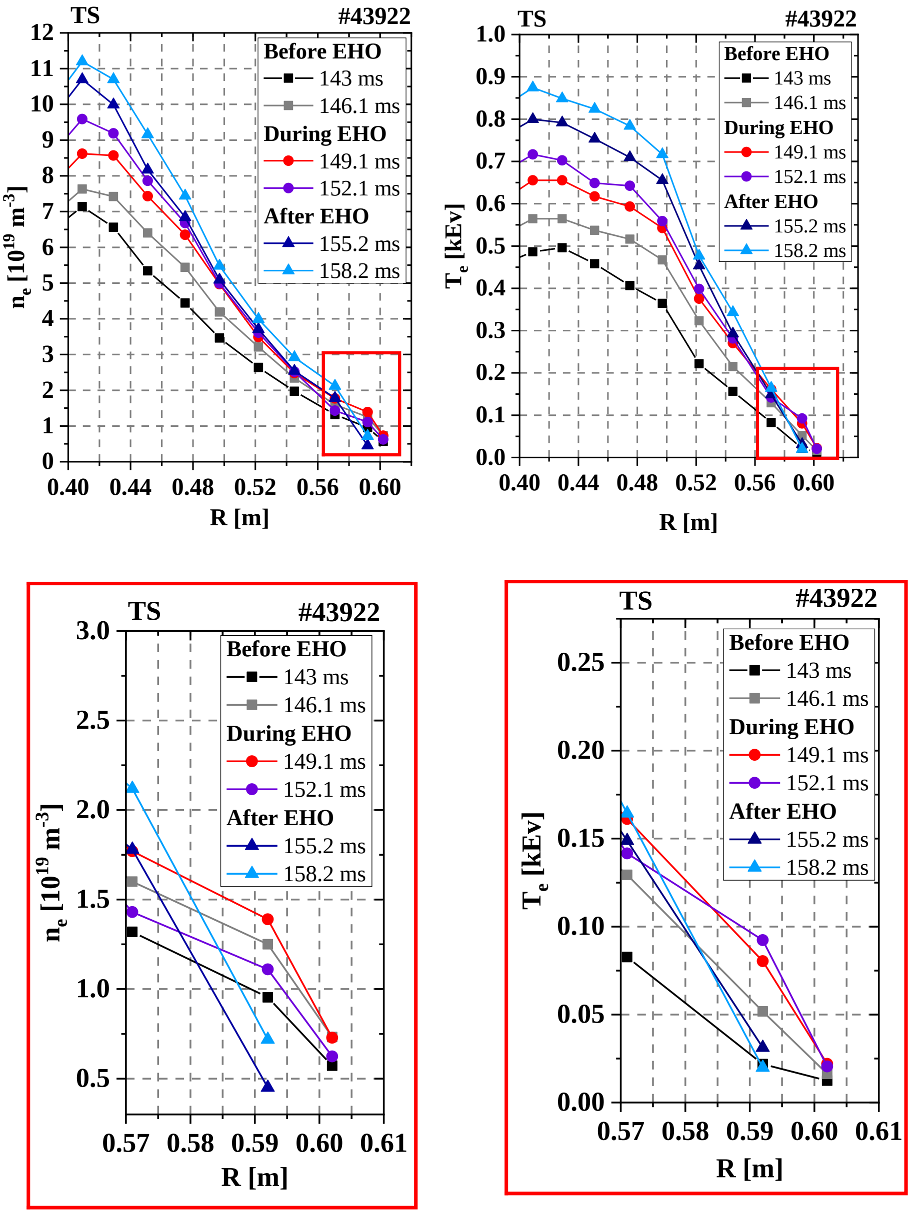

Figure 5. electron density n_e (left) and temperature T_e (right) profiles at different stages of the discharge.

It has been noted that the electron density n_e and temperature T_e measured by TS [20] increase gradually during the discharge, but there is a significant increase of electron density and temperature at the plasma edge at R = 0.58-0.60 m seen only during EHO. These observations are shown in the form of n_e and T_e profiles in Figure 5. While the n_e and T_e increase steadily at R = 0.4-0.56 m throughout the discharge, there is a noticeable increase of the n_e and T_e at R = 0.57-0.61 m only during the EHO stage of the discharge with the values decreasing after its disappearance. The area of the n_e and T_e increase coincides with the area where the EHO was detected using DBS. This observation may be related to the reconfiguration of the plasma current density profile, responsible for the development of peeling instability, and the corresponding displacement of the plasma discharge along the radius.

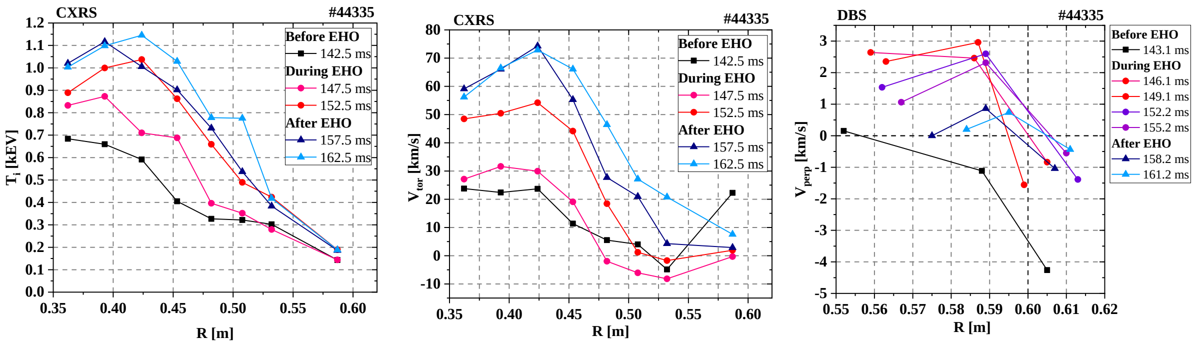

Figure 6. Radial profiles of (left) ion temperature T_i, (middle) toroidal rotation velocity V_{tor} and (right) perpendicular rotation velocity V_{perp}.

There are no significant changes in ion temperature at the plasma edge associated with EHO as measured by CXRS, but unfortunately, this observation could be a limitation of the diagnostic on Globus-M2. However, there is an overall increase of ion temperatures in the core throughout the discharge as shown in Figure 6.

A dramatic change of plasma rotation during EHO was observed (see Figure 6). There is a significant increase in values and change of direction of the perpendicular plasma rotation velocity in the area of EHO development. After the start of the EHO-like oscillations the V_{pol} values go from negative with values of about 1-4 km/s to positive reaching up to 3 km/s inside the region of EHO development at radii R = 0.56-0.61 m. This is accompanied by a simultaneous decrease of toroidal rotation (as well as the toroidal rotational shear) at the plasma edge, with the V_{tor} values increasing steadily both in the core and at the edge after the disappearance of the EHO.

4. REGIMES WITH EHO-LIKE OSCILLATIONS

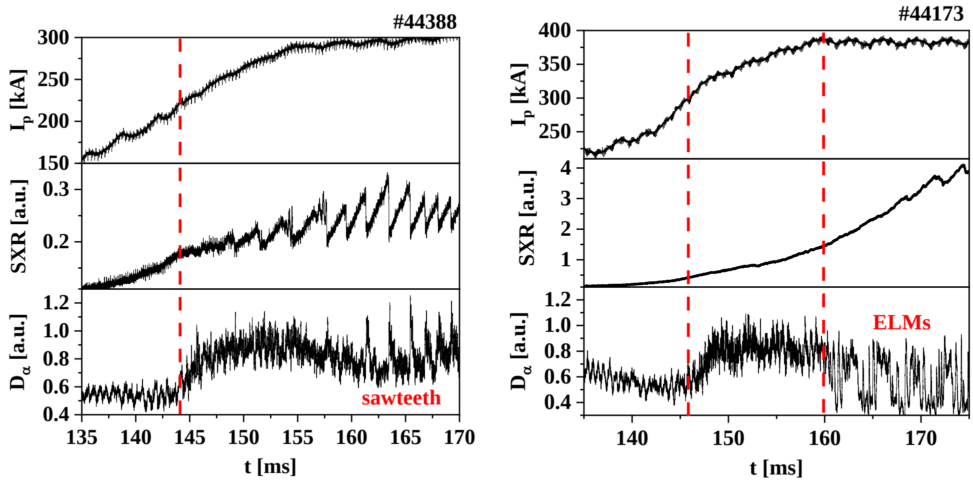

Figure 7. (from top to bottom) plasma current I_p, soft X-ray (SXR) and D_α signals for EHO regime with sawtooth oscillations (left) and ELMy H-mode (right)

In experiments on Globus-M2 several types of scenarios of the EHO were observed. The examples of such regimes are demonstrated in Figure 7. In some cases, the fluctuations exist for most of the discharge, despite the development of other modes such as sawteeth. The EHO can co-exist with sawtooth oscillations for prolonged periods of time. Under other conditions the EHO would disappear and be followed by a transition to an ELMy H-mode which stops their development. The study of the underlying differences in these regimes is the topic of future research.

5. PEELING-BALLOONING STABILITY

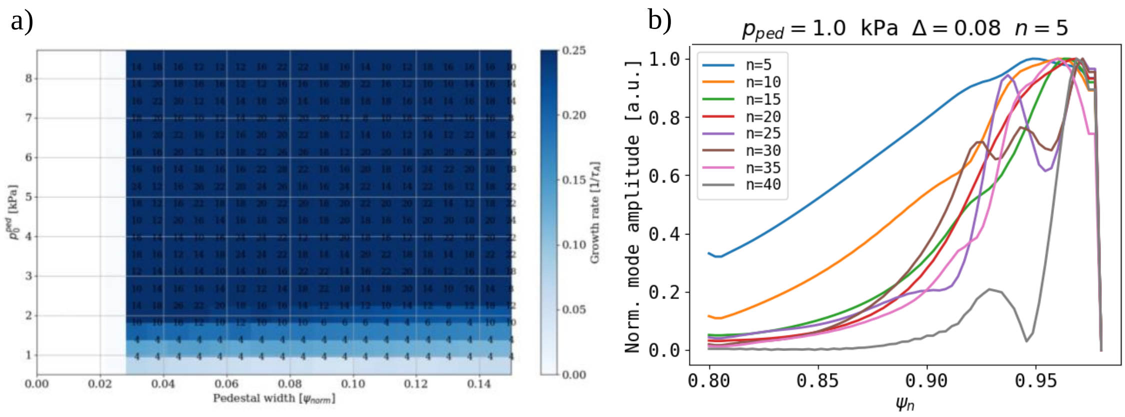

Figure 8. a) Growth rate of the peeling-ballooning instability and the toroidal number of the most unstable mode, b) the poloidal mode structure for the marginally stable simulation case with the dominant toroidal mode number n=5 at pedestal height p_{ped} = 1.0 kPa, pedestal width Δ=0.08, and triangularity δ=0.2 for discharge #44335.

The pedestal conditions during the EHO phase of the Globus-M2 discharge #44335 were close to the peeling-ballooning stability limit in the linear 3-field MHD simulations that used the BOUT++ code [21] (see Figure 8). The most unstable mode had low toroidal numbers (n=5). The nonlinear calculations demonstrated the poloidal mode structure span significantly inside the plasma, holding up to experimental observation of EHO-like oscillations inside the plasma confinement region.

ACKNOWLEDGEMENTS

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