

## Fast changes in the mode structure of chirping energetic particle driven modes

L. Horváth<sup>1</sup>, G. Papp<sup>2,3</sup>, G. I. Pokol<sup>1</sup>, Ph. Lauber<sup>3</sup>, G. Por<sup>1</sup>,

A. Gude<sup>3</sup>, V. Igoshine<sup>3</sup> and the ASDEX Upgrade Team<sup>3</sup>

<sup>1</sup> *Institute of Nuclear Techniques, Budapest University of Technology and Economics, Hungary*

<sup>2</sup> *Max-Planck/Princeton Center for Plasma Physics*

<sup>3</sup> *Max Planck Institute for Plasma Physics, Garching, Germany*

Supra-thermal energetic particles (EPs) in tokamak plasmas can excite various instabilities which can lead to an enhanced transport of fast particles. These instabilities constitute a non-linear system where kinetic and MHD non-linearities can both be important making it difficult to describe the phenomenon [1]. Several types of non-linear behaviour of the mode amplitude and frequency are observed on present-day tokamaks. This behaviour ranges from steady-state – where the amplitude saturates at nearly constant frequency – to an explosive growth. The type of behaviour is expected to significantly influence the impact of the instabilities on the fast particle transport. Thus, their thorough understanding from both experimental and theoretical side is essential.

Bursting beta induced Alfvén eigenmodes (BAEs) and EP-driven geodesic acoustic modes (EGAMs) are routinely driven unstable in the ramp-up phase of off-axis NBI heated plasmas in ASDEX Upgrade (AUG) [2]. The investigation of these bursting modes can provide important information about the underlying physics of the non-linear behaviour of EP-driven modes.

Our goal is to experimentally investigate the rapid changes in the radial structure of bursting EP-driven modes during the non-linear chirping phase. Due to diagnostic and data analysis complexities this task has never been accomplished before. Some modes are expected to retain their radial structure, while others would be expected to change. Even qualitative results can provide important information about the underlying physics and strengthen (or challenge) our present theoretical understanding. Furthermore, an analysis based on the methods developed here can serve as the basis of comparison with numerical codes which simulate the time evolution of EP-driven modes.

**Analysis principles** The only fluctuation measurement which has spatial resolution and these modes were visible in its signal was the SXR diagnostic. The ECE and the ECE imaging (ECEI) diagnostics would be good candidates due to their high time- and spatial resolution, however, BAEs and EGAMs were not visible by them in the investigated shots. Since the SXR diagnostic is a line-integrated measurement, it is not straightforward to reconstruct the radial structure of the mode, but many line-of-sights (LOSs) are available which makes it possible to qualitatively investigate the time evolution of the radial structure.

In general, the signal-to-noise ratio of the SXR measurements was poor. In many cases, modes which were clearly visible on the magnetic spectrogram were only visible on one or two LOSs of SXR. The strategy was to find cases where the mode is observable on at least 3 adjacent LOSs of a particular SXR camera. Finally, 3 cases for BAEs and 5 cases for EGAMs were found where the oscillation amplitude on the SXR signals was sufficiently high to identify them visually on the SXR spectrograms.

To examine the changes in the radial eigenfunctions, a radial mapping of the oscillation amplitudes was constructed. This means that each LOS was labelled with the normalized poloidal flux of the magnetic flux surface to which the LOS was tangential. The oscillation amplitude was calculated for each LOS and it is plotted as the function of the radial coordinate. This way the radial mapping of the oscillation amplitudes can be evaluated at any time instant. The oscillation amplitude were not normalized with the gradient of the background SXR radiation, because it did not change significantly during a chirp. The rapidly changing mode frequency and the low signal-to-noise ratio were handled with an advanced time-frequency transform based method [3].

**Beta-induced Alfvén eigenmodes** In the gaps of the shear Alfvén continuum weakly damped normal modes can exist. These gap modes can be easily excited by the EP population. The BAE gap is introduced by the coupling between compressible acoustic waves and the shear Alfvén continuum [4]. BAEs are driven by the radial gradient in the EP distribution function [5].

A magnetic spectrogram with downchirping BAEs is shown in figure 1a. A thorough mode number analysis [6] was carried out by using the magnetic pick-up coil system of AUG which showed that the observed BAEs have  $n = 1$  toroidal and  $m = -3$  poloidal mode number.

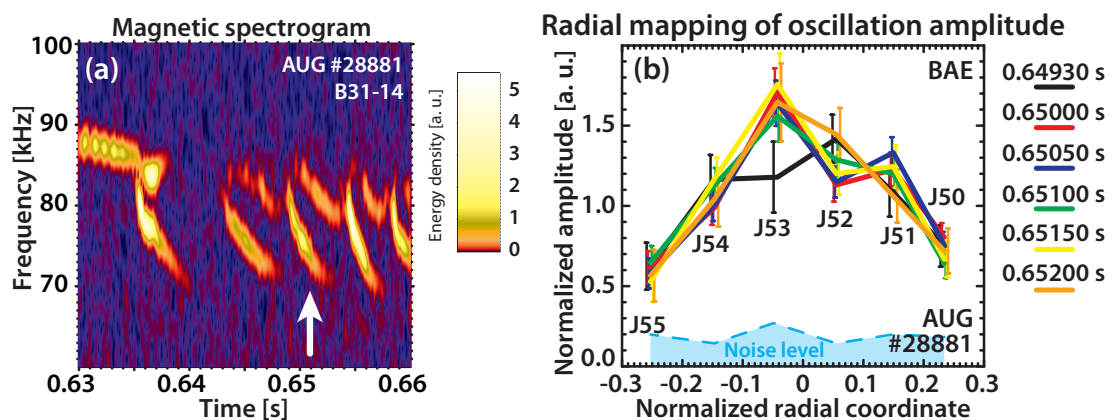


Figure 1: (a) Downchirping BAEs in the range of 70 – 85 kHz are visible on the magnetic spectrogram. (b) The radial mapping of the oscillation amplitude of BAEs on the different SXR LOSs.

The radial mapping for the chirp indicated with white arrow in figure 1a is presented in figure 1b. Since this work focuses on the relative changes in the radial structure of the modes, each curve of the radial mapping was normalized with its integral. The background noise level is estimated from time-frequency intervals of the SXR spectrograms where no coherent mode

appeared. The average of the background noise level of the different channels is also plotted in the radial mappings. The error bars were estimated from the background noise level by taking into account the error propagation in the amplitude reconstruction formula [7].

The time evolution of the radial structure is similar in all 3 cases to the one presented in figure 1b, i.e the results do not show significant changes in the radial distribution of the oscillation amplitudes. This suggests that if there is any change in the radial eigenfunction it is smaller than the uncertainty of our measurement. This observation is consistent with the physical picture that BAE is a normal mode of the plasma and its radial structure strongly depends on the background plasma parameters rather than on the EP distribution.

**Energetic particle driven GAMs** EGAM is an energetic particle mode which can be excited if the EP pressure is sufficiently high compared to the thermal pressure and the EP drive can overcome the continuum damping. Their mode structure is independent from the shear Alfvén continuum, and sensitively depends on the EP distribution. Their frequency usually correspond to a characteristic frequency of the EP orbital motion.

In figure 2a a magnetic spectrogram with upward chirping EGAMs is shown. In principle EGAMs should only be detectable with density fluctuation measurements because it is an electrostatic mode, however, due to sideband coupling it is clearly visible on magnetic fluctuation measurements as well [8]. According to the mode number analysis carried out by using the magnetic probe measurements the mode coupled to EGAMs (which allows to detect the mode in the magnetic fluctuation signals) have  $n = 0$  toroidal and  $m = -2$  poloidal mode number.

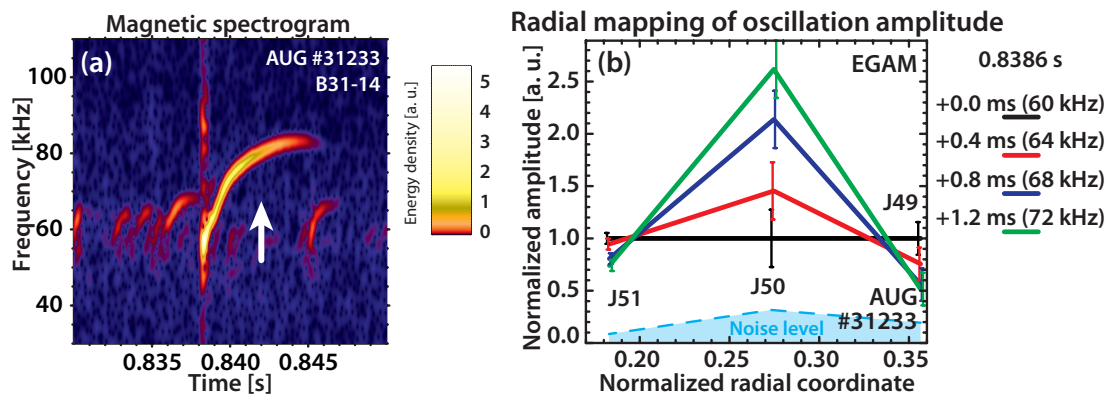


Figure 2: (a) Upchirping EGAMs in the range of 40 - 90 kHz are visible on the magnetic spectrogram. (b) The radial mappings of the oscillation amplitude of EGAMs in 3 SXR LOSs which are located above the magnetic axis.

The radial mapping for the chirp indicated with white arrow in figure 2a is presented in figure 2b. In this case the reconstructed amplitudes were normalized to the amplitude at the beginning of the chirp. Figure 2b shows the results of LOSs located above the magnetic axis. On LOSs located below the magnetic axis, radial mappings do not show any significant change in the mode structure. However, on LOSs located above the magnetic axis (figure 2b), a shrinkage of the mode is visible, since as time evolves the relative amplitude in the middle channel is rising

compared to the outer channels. This shrinkage of the EGAM radial structure was significant in all 5 investigated cases.

The observed shrinkage of EGAMs during the non-linear chirping phase is consistent with our present theoretical understanding. According to the EGAM resonance condition ( $\omega - \omega_t = 0$ ), the mode frequency is equal to the transit frequency of the interacting ions. The EGAM drive is proportional to the velocity phase space gradient in the EP distribution function. The coordinates of the steepest gradient determine the velocity phase space coordinates of the interacting particles. The mode frequency is rapidly increasing as it is visible in figure 2a. This means that as time evolves, the resonance condition changes and shifts to particles with higher transit frequency. The simulated EP distribution (TRANSP [9]) showed that the resonance condition moves toward more passing particles during the non-linear phase. Since the radial structure of EGAMs is determined by the orbit of the interacting ions and more passing particles have a narrower orbit width, the experimentally observed shrinkage of the radial mode structure can be explained.

**Conclusions** Our analysis showed that in case of the observed downward chirping BAEs the changes in the radial structure were smaller than the uncertainty of the measurement. This behaviour is consistent with that the radial structure of BAEs – as normal modes – strongly depends on the background plasma parameters rather than on the EP distribution.

In case of rapidly upward chirping EGAMs the analysis consistently shows shrinkage of the mode structure. This can be explained by the changing resonance condition in the velocity phase space of EPs. The mode structure of EGAMs is sensitive to the EP distribution. The rising frequency of the mode indicates that, as time evolves, the EGAM is driven by more passing particles which have narrower orbit width. This leads to the experimentally observed shrinkage of the mode structure.

*Authors at BME NTI acknowledge the support of the Foundation for Nuclear Engineers (JNEA) and Hungarian State grant NTP-TDK-14-0022. This work has been carried out with support of FuseNet, the European Fusion Education Network. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.*

## References

- [1] W. W. Heidbrink, *Physics of Plasmas* **15**, 055501 (2008)
- [2] Ph. Lauber et al., Presented at the [13th IAEA TCM](#), Beijing, China (2013)
- [3] L. Horváth et al. 41st EPS Conference on Plasma Physics **38F**, P2.008 (2014)
- [4] A. D. Turnbull et al., *Physics of Fluids B*, **5**, 2546-2553 (1993)
- [5] C. Nguyen et al., *Plasma Physics and Controlled Fusion* **51**, 095002 (2009)
- [6] L. Horváth, *Reducing systematic errors in time-frequency resolved mode number analysis*, submitted to *Plasma Physics and Controlled Fusion*, [arXiv:1506.04864](#) (2015)
- [7] L. Horváth, *Analysis of fast ion induced instabilities in tokamak plasmas*, MSc thesis, Budapest University of Technology and Economics, [arXiv:1506.05134](#) (2015)
- [8] Ph. Lauber, *Physics Reports*, **533**, 33-68 (2013)
- [9] A. Pankin, *Computer Physics Communications*, **159**, 157-184 (2004)