*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-1.139 (2007)*

TAE internal structure through high-resolution soft x-ray measurements in ASDEX-Upgrade

P. Piovesan[1], V. Igochine[2], P. Lauber[2], K. Sassenberg[2,3], A. Flaws[2], M. García-Muñoz[2], S. Günter[2], M. Maraschek[2], L.Marrelli[1], P. Martin[1], P. McCarty[3], and the AUG team

[1] *Consorzio RFX, Euratom-ENEA Association, Padova, Italy*

[2] *Max-Planck-Institute für Plasmaphysik, EURATOM Association, Garching, Germany*

[3] *Department of Physics, University College Cork, EURATOM-DCU Association, Cork, Ireland*

We present a study on the internal structure of Toroidal Alfvén Eigenmodes (TAE) in ASDEX- Upgrade (AUG), using a soft x-ray multichord diagnostic with high spatiotemporal resolution (sampling rate up to 2*MHz*). In these experiments TAEs are induced by Ion Cyclotron Resonant Heating (ICRH) in both L-mode and H-mode plasmas. The eigenfunctions of multiple TAEs are measured and compared with predictions from the CASTOR code. The evolution of the TAE eigenfunctions is also followed in time across sawteeth.

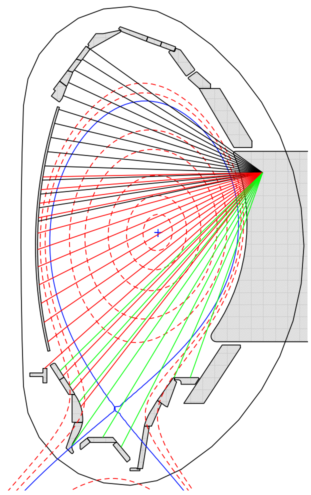

Figure 1: Schematic of the fast (2*MHz* sampling rate) lines of sight of the soft x-ray diagnostic.

Due to the high frequency of the TAEs and to their complex spatial structure, measurements of their eigenfunctions at sufficient resolution started becoming feasible only recently. Accurate measurements have been obtained in DIII-D with a fast ECE diagnostic [M.A. Van Zeeland *et al.*, PRL **97**, 135001 (2006)].

The AUG soft x-ray diagnostic has been recently upgraded and has now a spatiotemporal resolution sufficient to measure the internal structure of Alfvénic instabilities. The diagnostic consists of 30 lines of sight with 2*MHz* sampling frequency, which are shown in the AUG poloidal cross-section in Fig. 1, and of 98 channels with 0.5*MHz* sampling frequency. Only the faster channels are used in the present work, since in the plasmas studied so far the TAE frequency was very close to the frequency bandwidth of the slower channels.

A typical ICRH discharge is shown in Fig. 2. In the first part of the current flattop, $1-2s$, the ICRH power is ramped up to $6MW$ and then maintained constant through the entire discharge, which stays in L-mode. ICRH is transiently turned off at $3s$ and $4s$, when Neutral Beam Injection (NBI) is turned on for short periods to allow Motional Stark Effect (MSE) measurements. MSE data are used to accurately reconstruct the magnetic equilibrium with the CLISTE code, which is used to map the soft x-ray lines of sight geometry and constrain the CASTOR simulations.

Fourier spectrograms of an edge magnetic probe and of a soft x-ray signal are also shown in Fig. 2. The soft x-ray line of sight in this case has an impact parameter $\rho_{pol} \simeq 0.5$ and intersects the region where the TAE eigenfunction has its maximum. The TAEs have frequencies in the range $150-200kHz$ and are destabilized when ICRH exceeds a threshold power of about $2.5MW$. The three dominant TAEs in this discharge have toroidal mode number $n = 4,5,6$, as determined from phase delay analysis of pick-up coils placed at different toroidal angles. Lower toroidal mode numbers correspond to lower TAE frequencies. The TAE amplitudes are modulated by sawteeth with an average period of about $30ms$. Other lower frequency modes are also visible in the spectrograms and are identified as $m = 1, n = 1$ kinks and fishbones. Moreover a coherent mode with frequency of about $60kHz$ is present, whose analysis is beyond the scope of this paper [M. García-Muñoz *et al.*, submitted to PRL].

Let us now focus on the effect of the TAE modes on the soft x-ray emission. Fig. 2 shows that not all the TAE peaks present in the magnetic spectrogram are also visible in the soft x-ray one. Random noise in the SXR channels can partly hide the TAE peaks at these high frequencies. Cross-correlation with the magnetic signals, which have a much larger signal-to-noise ratio, is very effective in cleaning this noise. The soft x-ray fluctuation amplitude associated with each TAE mode is computed in the following way: $\tilde{A}_{sxr} = \sqrt{2\int_{\Delta f} P_{sxr}(f)\,\gamma^2_{mag-sxr}(f)\,df}$, where $\gamma_{mag-sxr} = |P_{mag-sxr}(f)|/\sqrt{P_{mag}(f)P_{sxr}(f)}$ is the coherence function, $P_{mag}(f)$ and $P_{sxr}(f)$ the Fourier power spectra of the magnetic and soft x-ray signals, $P_{mag-sxr}(f)$ their cross-power spectrum, and the inte-

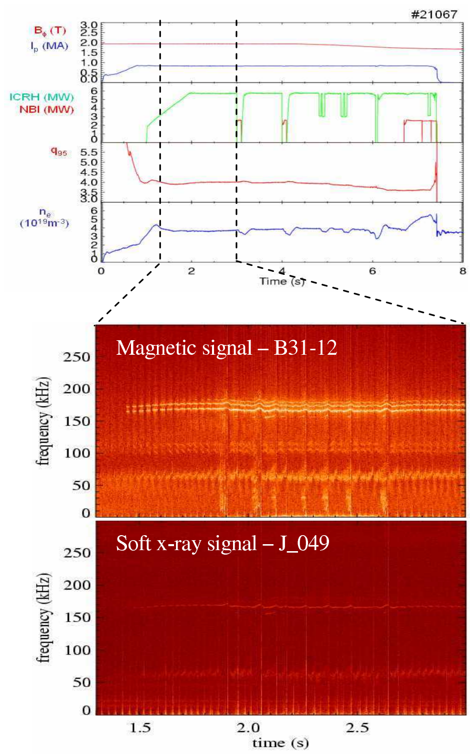

Figure 2: Waveforms of the ICRH discharge #21067 and Fourier spectrograms of a magnetic and a soft x-ray signal.

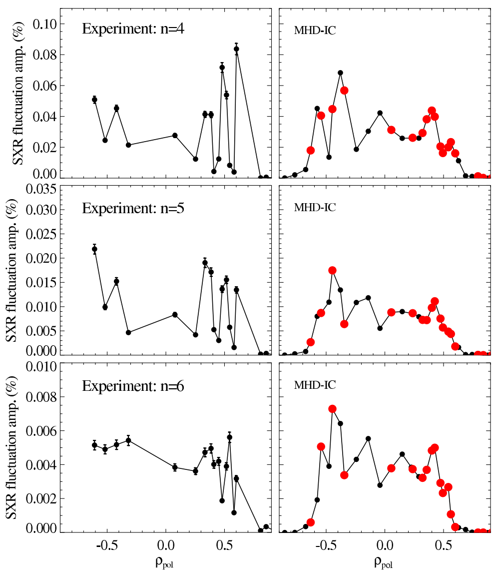

Figure 3: Experimental (left) and simulated (right) soft x-ray fluctuation profiles for the $n = 4,5,6$ TAEs in discharge #21067, $t = 2.85sec$.

gral is extended to an interval Δf around the TAE frequency peak.

This method is used to compute the radial profile of the soft x-ray fluctuation amplitude associated with each TAE. Fig. 3 (left column) reports the results of this analysis for the $n = 4,5,6$ TAEs in discharge #21067 at $t = 2.85s$. The profiles are time averaged over a period of $200ms$ including several sawteeth. The TAE displacement profile is computed from the soft x-ray fluctuation profile as $\xi_r(\rho_{pol}) = -\tilde{A}_{sxr}/\nabla_\rho A_{sxr}$, where $A_{sxr}(\rho_{pol})$ is the mean soft x-ray brightness profile. Typical TAE displacement values in these discharges are in the range $\xi_r \simeq 0.2-0.6mm$. The TAE profiles have their maxima at about $\rho_{pol} \simeq 0.5$ and decrease to zero at larger radii. The core TAE magnetic perturbation can be estimated as $\delta b_r/B_0 = \xi_r/(2qR_o) \simeq 0.5-2\times10^{-4}$, which is similar to the values recently found in DIII-D with fast ECE.

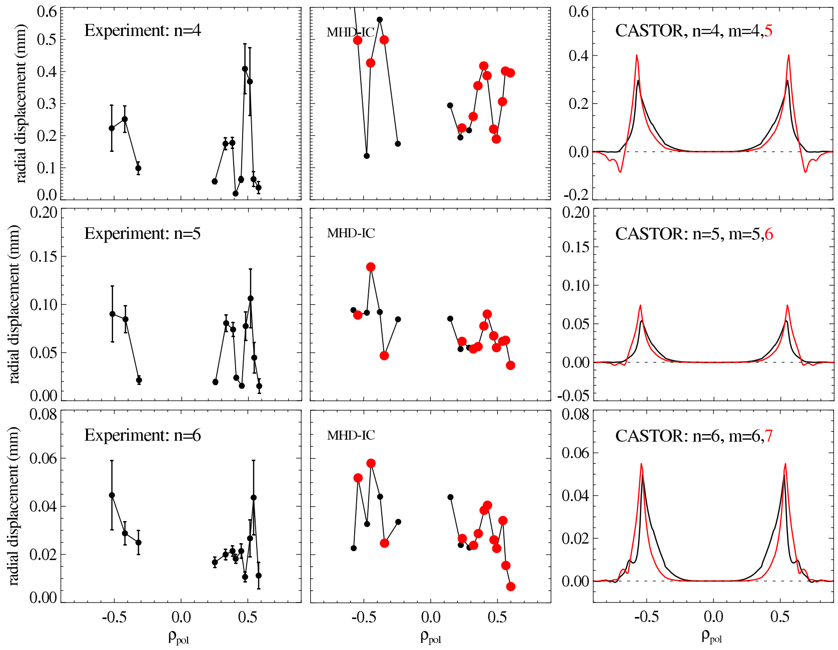

Figure 4: Radial displacement profiles for the $n = 4,5,6$ TAEs in discharge #21067, $t = 2.85s$. Experimental profiles (left column) are compared with profiles simulated with MHD-IC (central column) using CASTOR eigenfunctions in input (right column).

To compare the measured TAE profiles with the predictions from the MHD code CASTOR, the soft x-ray signals are simulated with the MHD-Interpretation Code [V. Igochine *et al.*, Nucl. Fusion **43**, 1801 (2003)]. In this case MHD-IC receives in input the mean kinetic profiles, the magnetic equilibrium and the TAEs eigenfunctions predicted by CASTOR. The code then simulates the soft x-ray signals, taking into account the real diagnostic geometry. The TAE profiles are computed from these synthetic signals in the same way as the experimental ones. The results are reported in Fig. 3 and 4 along with the CASTOR eigenfunctions used in the simulation. The red dots mark the subset of channels available in this particular discharge. Only the two dominant poloidal harmonics m and $m+1$ are used, since it has been verified that the contribution from higher-m harmonics is negligible.

The model reproduces quite well several features observed in the experiment, and in particular the overall shape of the TAE profiles and the radial position of the maxima at mid radius. These maxima reflect the position of the TAE gap, where the two dominant poloidal harmonics m and $m+1$ are located. A sensitivity test has been made by varying the position and radial width of the TAE eigenfunctions in MHD-IC. A shift of the radial position changes the radius where the TAE profiles decrease to zero. If the radial width is doubled, the simulated profiles become centrally peaked and are no more compatible with the experimental ones.

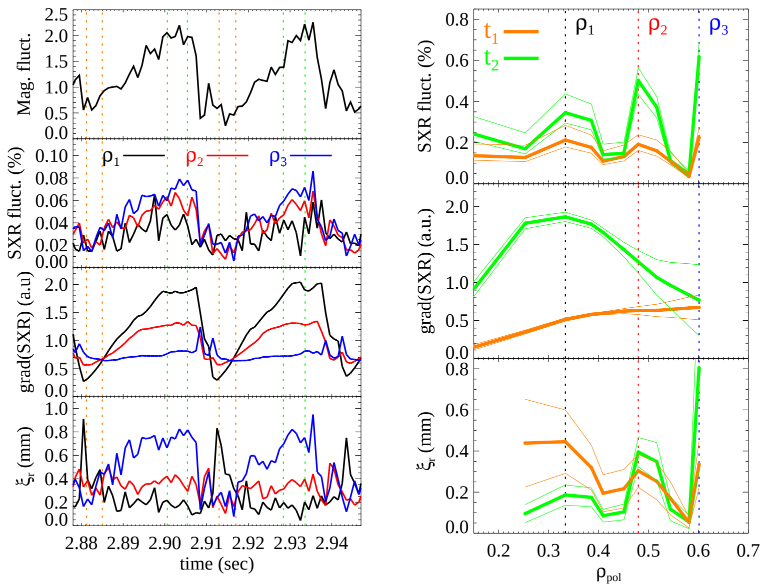

Figure 5: Temporal evolution of the $n = 4$ TAE profiles across sawteeth in discharge #21067.

The good resolution of the soft x-ray diagnostic allowed to characterize the temporal dynamics of the TAE modes. In Fig. 5 we report their evolution across sawtooth crashes in discharge #21067. The $n = 4$ TAE profiles are compared before and after a sawtooth crash (right column) and the time evolution of the TAE displacement is shown at the three radii $\rho_1 = 0.33$, $\rho_2 = 0.48$ and $\rho_3 = 0.6$ (left column). The displacement profile changes its shape after the sawtooth crash shifting to smaller radii, but its absolute value does not change significantly. The shift in radial position is compatible with the change of the safety factor profile at a sawtooth crash, since $q_{TAE} = (m+1/2)/n$ is fixed and the on-axis q profile could be shifted up. The fact that the displacement value does not change too much suggests that the fast ion profile, which is the main TAE drive, may be not largely affected by the sawtooth crash. This hypothesis will be checked with more precise simulations and measurements.

Acknowledgement. This work was supported by the European Communities under the contract of Association between EURATOM/ENEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.