TAEs excited by ICRH beatwaves in the ASDEX Upgrade Tokamak

K. Sassenberg[1,2], M. Maraschek[1], P. J. Mc Carthy[1,2], W. Bobkov[1], M. García-Muñoz[1], N. Hicks[1], V. Igochine[1], P. Lauber[1], S. Günter[1], ASDEX Upgrade Team.[1]

[1] *Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching, Germany.*

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

Introduction

At ASDEX Upgrade (AUG) Toroidicity induced Alfvén Eigenmodes (TAEs) are typically excited by fast ions accelerated by Ion Cyclotron Resonance Heating (ICRH)[1]. However, TAEs can also be driven to a finite amplitude using ICRH beatwaves[2]. Several potential mechanisms have been proposed by Fasoli et al.[3], which can lead to the creation of a beatwave capable of driving AEs. At AUG, separate ICRH antenna-generator groups emit waves at different frequencies which couple non-linearly in the plasma to form the beatwave (bw) at the frequency difference Δf, where $f_{bw} = \Delta f$, leading to either a classical three wave coupling between the two ICRH waves and the TAE or the creation of a virtual antenna in the plasma which drives the TAE[3]. To drive TAEs, the beatwave frequency f_{bw} must match the mode's frequency in the lab frame ($f_{bw} \simeq f^{lab}_{TAE}$), and in the case of a three wave coupling, the difference between the wave numbers of the ICRH waves $\Delta k = k_{bw}$ must match the TAEs parallel wave number $k_{\parallel TAE}$ ($k_{bw} \simeq k_{\parallel TAE}$)[3].

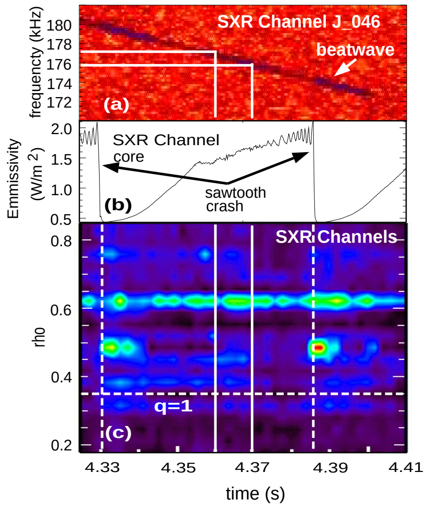
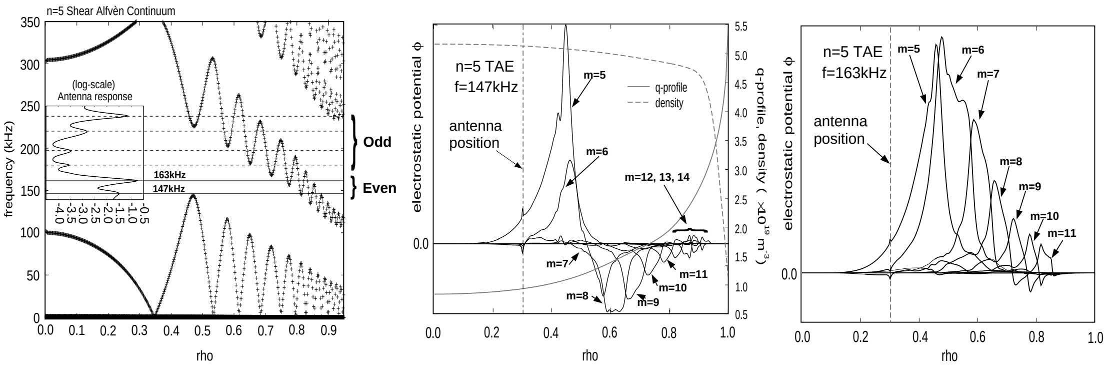


Figure 1: AUG discharge 23814: (a) Spectrogram - SXR emissivity at $\rho = 0.6$. (b) SXR emissivity $\rho = 0.1$. (c) Emissivity of all SXR channels along the tracked beatwave frequency.

In the absence of a sufficient fast ion drive an ICRH beatwave can drive TAEs to a finite amplitude, and increase the amplitude, and thereby influence the stability, of fast ion excited TAEs. This provides the means to excite specific TAEs, from a large range of toroidal mode numbers, n, using existing ICRH harware throughout a discharge without significantly perturbing the plasma state, thus facilitating an indepth analysis of TAE stability through diagnosis of the safety factor q profile using MHD-Spectroscopic techniques[6]; and to study the influence of TAEs on the fast ion population.

Exciting Stable TAEs

In discharge #23814 the intrinsic fast ion drive of ICRH is insufficient to overcome damping and excite TAEs. The beatwave can provide the energy necessary to drive modes, which would otherwise remain stable. The plasma parameters for the prototypical discharge were, toroidal magnetic field $B_{tor} = -2$T, plasma current $I_p = 0.83$MA, central line-integrated density $\bar{n}_e = 5 \times 10^{19}\mathrm{m}^{-3}$, ICRH power $P_{ICRH} = 2.5$MW, Electron Cyclotron Resonance Heating (ECRH) power $P_{ECRH} = 1.3$MW, total radiated power $P_{rad} = 3.7$MW, $q_0 \leq 1.0$ and $q_{95} = 4.2$. q_0 and q_{95} are the safety factor q values at the magnetic axis and at the flux surface containing 95% of the poloidal flux respectively. In figure 1 (a), the beatwave is seen in a spectrogram of the Soft X-Ray (SXR) camera[5] channel J_{046} emissions at $\rho = 0.6$. Part b shows the SXR channel



(a) Alfvén Continuum

(b) Resonance at 147kHz with experimentally derived density and safety factor q profiles.

(c) Resonance at 163kHz

Figure 2: AUG discharge 23814: n=5 TAE Continua and Electrostatic potential eigenfunctions.

I_{055} emissions at $\rho = 0.1$. The emissivity of all SXR channels in a poloidal plane at the tracked beatwave frequency is plotted in part c versus time and ρ, where ρ is the normalised poloidal flux radius. Sawtooth crashes typically accompany the use of ICRH power and therefore the beatwave driven MHD activity observed in figure 1 (c) were classified into two groups: those driven purely by the beatwave from 4.36s-4.37s; and those coinciding with the sawtooth crashes at t=4.330s and t=4.386s, possibly driven by the combination of the beatwave and additional fast ions expelled from within the q=1 surface by the sawtooth crash. At approximately 4.365s an n=5 resonance at 177kHz driven by the beatwave is seen to extend across a significant fraction of the minor plasma radius and to be separate from the sawtooth crashes. Correcting the measured frequency for a plasma rotation frequency of 5kHz, calculated from the doppler-shifted frequencies of fast ion excited TAEs in a discharge with similar plasma parameters shown in figure 4, the mode's plasma rest frame frequency was found to be 152kHz[2].

LIGKA simulations [4], displayed in figure 2(a), identified two candidate n=5 TAEs at 147kHz and 163kHz, respectively. The electrostatic potential eigenfunctions corresponding to the resonances are displayed in figures 2(b) and 2(c). An even eigenfunction which changes sign at $\rho \simeq 0.5$ was predicted for the resonance at 147kHz. Similar results were found for the resonance at 163kHz, however, without a sign change in its eigenfunction. A Radial Displacement Eigenfuncion (RDE) was reconstructed from SXR measurements at t=4.36s using the formula $\xi(\rho,t) = |(I(\rho,t) - \langle I_0 \rangle(\rho))/\nabla(\langle I_0 \rangle(\rho))|$[5] and is shown in figure 3 in addition to the RDE envelopes calculated by LIKGA. $I(\rho,t)$ is the emissivity of a particular channel, and $\langle I_0 \rangle(\rho)$ is the emissivity averaged over several periods of the mode. Here the RDE envelope calculated from the SXR data is seen to have a deep local minimum at $\rho \simeq 0.6$, a maximum displacement in the range 2-4mm and extends radially from $\rho \simeq 0.2$ to $\rho \simeq 0.8$. This shows the best agreement with the RDE envelope calculated by LIGKA for the resonance at 147kHz shown in figure 3 (b). Furthermore an analysis of the driven mode's poloidal magnetic amplitude distribution identified an even character[1][2] consistent with the character of the eigenfunctions shown in figure 2(b), and a fractional amplitude of $\tilde{B}/B \simeq 10^{-6}$ which will not significantly perturb the plasma[3]. Once the RDE of each TAE excited by ICRH beatwaves has been reconstructed several points of safety factor profile information can be extracted and used to constrain the plasma equilibrium reconstruction[7].

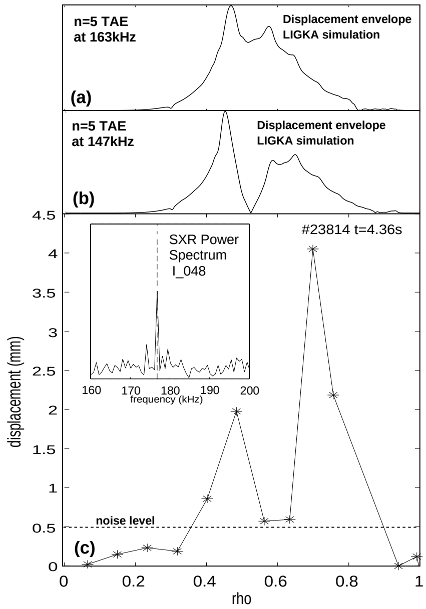


Figure 3: RDE envelopes for the n=5 TAEs at (a) 163kHz and (b) 147kHz. (c) RDE envelope calculated from SXR data at t=4.36s. (Insert) Corresponding power spectrum showing beatwave excited mode at 177kHz

Influencing the stability of existing TAEs

In discharge #23805, the plasma parameters were similar to those in #23814 with the exception of a lower $P_{rad} = 2.5$MW as a result of a lower high-Z_{eff} impurity content. This produced a fast ion drive sufficient to overcome damping and excite TAEs. In figure 4 (a) the fast ion excited n=4 TAE frequency coincides with the ICRH beatwave frequency at 1.38s, $f_{bw} = f^{lab}_{TAE}$. In parts (b,c) the tracked amplitudes of the n=4,5,6 TAEs and beatwave are shown. The plasma rest frame frequency f_{TAE} of these modes and the plasma rotation frequency are 178kHz and 5kHz, respectively. At the coincidence, the mode's phase is clearly identifiable as n=4, therefore the amplitude increase is not simply the superposition of two non-interacting magnetic fields.

This interaction leads to a transfer of power from the beatwave to the resonant TAE resulting in an increase in amplitude $\delta\tilde{B}$ above the TAE's saturated amplitude $\tilde{B}_{sat}$, where $\delta\tilde{B}$ is comparable to $\tilde{B}_{sat}$ in magnitude and $\delta\tilde{B}/B \simeq 10^{-4}$. Here $\tilde{B}_{sat}$ is the maximum amplitude due solely to the ICRH accelerated fast ion drive as identified for times when f_{bw} and f_{TAE} do not coincide. The n=5,6 TAEs also experience an amplitude increase. A non-linear coupling of the TAEs, due to their close proximity to each other radially, allows the beatwave power to be shared. This shows an ICRH beatwave can also be used to influence the stability fast ion excited TAEs allowing their effect on the fast ion population to be studied.

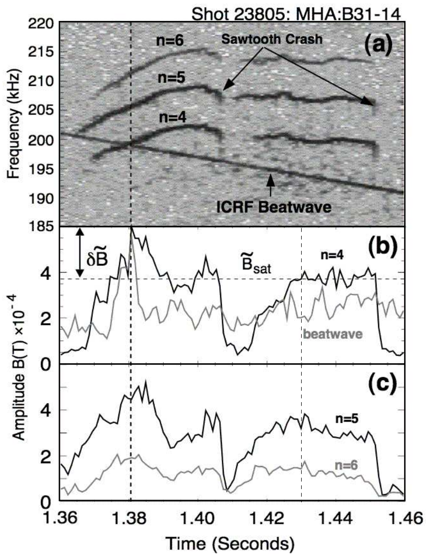


Figure 4: AUG discharge 23805: (a) Magnetic spectrogram. Tracked amplitudes (b) n=4 TAE and beatwave and (c) n=5,6 TAEs.

Conclusions

The work presented shows the successful reconstruction of the RDE structure and subsequent identification of an ICRH beatwave excited TAE from SXR measurements. The doppler corrected frequency, radial structure and extent of the reconstructed RDE was found to show good agreement with the eigenfunction predicted by the gyro-kinetic code LIGKA. Furthermore, magnetic probe measurements independently confirmed the even character of the identified TAE, and showed ICRH beatwaves provide the means of exciting TAEs, which can be used to either diagnose the safety factor q profile without significantly perturbing the plasma state, or to influence the stability of TAEs already excited by fast ions allowing their effect on the fast ion population to be studied.

References

[1] K. Sassenberg et al., Plasma Physics and Controlled Fusion, 51, 065003 (2009).

[2] K. Sassenberg et al., Nuclear Fusion, 50, 052003 (2010).

[3] A. Fasoli et al., Nuclear Fusion, 36, 258-263 (1996).

[4] P. Lauber et al., Journal of Computational Physics, 226, 447-465 (2007).

[5] V. Igochine, et al., Nuclear Fusion, 43, 1801-1812 (2003).

[6] A. Fasoli et al., Plasma Physics and Controlled Fusion, 44, B159-B172 (2002).

[7] P. J. McCarthy, Physics of Plasmas, 6, 3554-3560 (1999).