

LETTER TO THE EDITOR

# ICRH Beatwave excited Toroidicity induced Alfvén Eigenmodes in ASDEX Upgrade

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**Abstract.** Experimental evidence is presented demonstrating that an Ion Cyclotron Resonance Heating (ICRH) beatwave can drive Toroidicity induced Alfvén eigenmodes (TAEs) to a finite amplitude and also increase the amplitude of TAEs already excited by fast ions. The radial structure of beatwave driven TAEs reconstructed from Soft X-Ray measurements are shown to agree with simulations from the gyro-kinetic code LIGKA. Thus beatwaves provide the means to excite TAEs which can be used to diagnose the plasma's safety factor profile through MHD-spectroscopic techniques without significantly perturbing the plasma or to influence the stability of existing TAEs allowing their effect on the fast ion population to be studied.

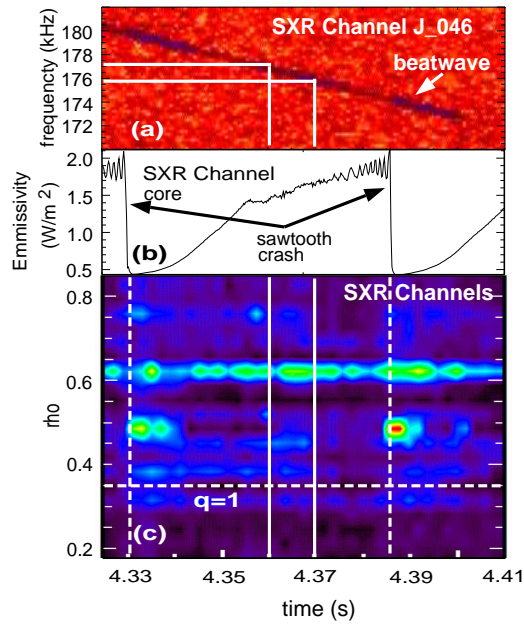
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Given sufficiently large fast ion energies and pressure gradients in a fusion plasma device, Alfvén Eigenmodes (AEs) will be destabilised, causing increased radial transport of fast ions[1][2][3]. The loss of these ions reduces plasma heating and may cause damage to plasma facing components in the vacuum vessel. Therefore a good understanding of AE stability properties and radial structure will be especially important in future fusion devices like ITER[4].

An important class of weakly damped AEs in a tokamak plasma, known as Toroidicity induced Alfvén Eigenmodes (TAEs), exists in the toroidicity induced gaps in the shear Alfvén continuum[1][2][5]. Associated with these gap modes is the frequency  $f_{gap}(\rho) = v_a(\rho)/4\pi q(\rho)R_0$ , where  $v_a(\rho) = B/\sqrt{\mu_0\rho_m(\rho)}$  is the Alfvén velocity profile,  $B$  is the magnetic field,  $\rho_m(\rho)$  is the mass density profile,  $q(\rho)$  is the safety factor profile,  $\rho$  is the normalised poloidal flux radius and  $R_0$  is the major radius. At ASDEX Upgrade (AUG) TAEs are usually excited by fast ions accelerated by Ion Cyclotron Resonance Heating (ICRH)[6]. However, TAEs can also be driven to a finite amplitude using ICRH beatwaves. Several potential mechanisms have been proposed by Fasoli et al.[7], 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  $\Delta f$ , 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[7]. To drive TAEs, the beatwave frequency  $f_{bw}$  must match the mode's frequency in the lab frame ( $f_{bw} \simeq f_{TAE}^{lab}$ ), 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  $k_{||TAE} = 1/2q_{TAE}R_0$  ( $k_{bw} \simeq k_{||TAE}$ )[7]. Experimentally, the beatwave frequency is repeatedly swept at a constant rate of 105kHz/s through the TAE frequency gap in the Alfvén continuum for the duration of the discharge.

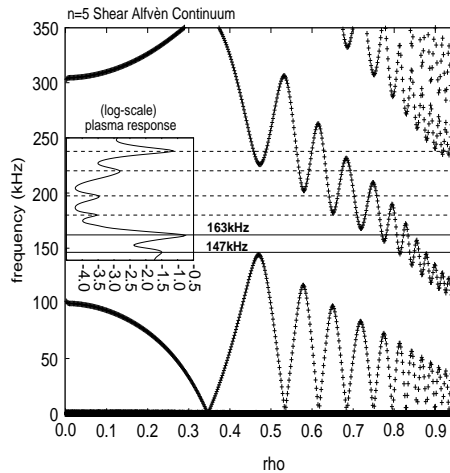
Experimental evidence is presented demonstrating that an ICRH beatwave can (1) drive TAEs to a finite amplitude in the absence of a sufficient fast ion drive and (2) increase the amplitude, and thereby influence the stability, of fast ion excited TAEs. In particular, the radial structure and extent of beatwave driven TAEs reconstructed from Soft X-Ray (SXR)[8] measurements were compared to and found to show good agreement with simulations from the gyro-kinetic code LIGKA[9]. This provides the means to excite specific TAEs, from a large range of toroidal mode numbers,  $n$ , using existing ICRH hardware 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[10]; and to study the influence of TAEs on the fast ion population. To achieve this, a beatwave power scan consisting of a set of 10 discharges was performed to define the TAE stability threshold from which prototypical examples of beatwave driven TAE activity above and below the TAE stability threshold are presented.

In discharge #23814 the intrinsic fast ion drive of ICRH is insufficient to overcome damping and destabilise TAEs. The beatwave can provide the necessary energy



**Figure 1.** (Colour) AUG discharge 23814: (a) Beatwave as seen in a spectrogram from the central SXR channel  $J_{046}$  at  $\rho = 0.6$ . (b) Emissivity of the central SXR channel  $I_{055}$  at  $\rho = 0.1$ . (c) Emissivity of all SXR channels along the tracked beatwave frequency.

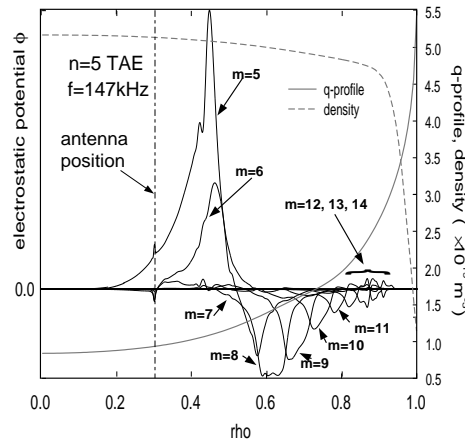
to drive modes, which are marginally stable, above the stability threshold. The plasma parameters for the prototypical discharge were, toroidal magnetic field  $B_{tor} = -2T$ , plasma current  $I_p = 0.83MA$ , central line-integrated density  $\bar{n}_e = 5.2 \times 10^{19}m^{-3}$ , ICRH power  $P_{ICRH} = 2.5MW$ , Electron Cyclotron Resonance Heating (ECRH) power  $P_{ECRH} = 1.3MW$ , total radiated power  $P_{rad} = 3.7MW$ ,  $q_0 \leq 1.0$  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 to scan from the top left at 180.5kHz to the bottom right of the image at 173kHz in a spectrogram of a central SXR camera[8] channel  $J_{046}$ , which measures the line-integrated emissivity along a line of sight tangent to the  $\rho = 0.6$  flux surface at a sampling rate of 2MHz. Part b shows the total emissivity of the SXR channel  $I_{055}$  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 the tangency radius  $\rho$  of each line of sight. 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  $t=4.386s$  (as indicated by the dashed lines), possibly driven by the combination of the beatwave and additional fast ions expelled from within the  $q=1$  surface by the sawtooth crash. In the time interval 4.36-4.37s, indicated by the solid vertical lines, an  $n=5$  resonance (determined from a linear least squares fit to the mode's phase measured by a toroidal array of mirnov probes) in the range 176kHz-177kHz (horizontal



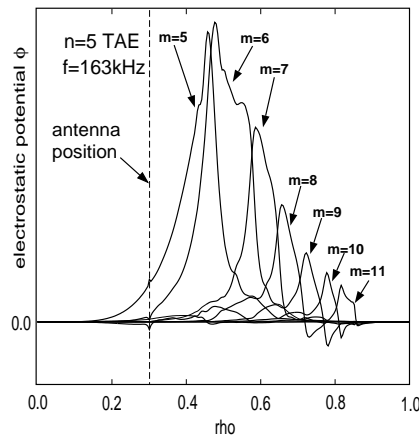
**Figure 2.** AUG discharge 23814: LIGKA n=5 shear Alfvén continuum with the plasma response at a range of driving antenna frequencies (log-scale) at  $t=4.36s$ . The solid horizontal lines identify the n=5 resonances at 147kHz and 163kHz (plasma rest frame), respectively.

markers figure 1(a)) extending across a significant fraction of the minor plasma radius and separate from the sawtooth crashes is driven by the beatwave. Extrapolating the measured frequency to the plasma rest frame to correct for a plasma rotation frequency of 5kHz, as measured in a discharge with similar plasma parameters containing fast ion excited TAEs shown in figure 7, a frequency of 152kHz was found[6].

Simulations displayed in figure 2, performed using the LIGKA code, found two candidate n=5 TAEs at 147kHz and 163kHz, respectively. In the simulations, an artificial driving antenna was placed at  $\rho = 0.3$  following from the assumption that the beatwave would have its maximum in the vicinity of the ICRH resonance in the plasma core. The electrostatic potential  $\phi = \sum_m \phi_m(\rho) e^{-i2\pi ft - im\theta + in\varphi}$  eigenfunctions corresponding to the resonances at 147kHz and 163kHz are displayed in figures 3 and 4 with the experimental q and density profiles, and are proportional to the corresponding Radial Displacement Eigenfunctions (RDE)[11]. Here m is the poloidal mode number, and  $\theta$  and  $\varphi$  are the poloidal and toroidal angles respectively. An even eigenfunction[12] 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. To identify which eigenfunction matches the observed resonance, an RDE was reconstructed from SXR measurements at  $t=4.36s$ . As is typical for many tokamak regimes, the density profile here is approximately constant over a large fraction of the minor radius (see figure 3,  $0.0 \leq \rho \leq 0.9$ ) reducing the SXR emissivity to a function of the electron temperature  $T_e$ . Therefore the RDE can be reconstructed using the following formula  $\xi(\rho, t) = |(I(\rho, t) - \langle I_0 \rangle(\rho)) / \nabla(\langle I_0 \rangle(\rho))|$ [8].  $I(\rho, t)$  is the emissivity of a particular channel, and  $\langle I_0 \rangle(\rho)$  is the emissivity averaged over several periods of the mode. The reconstructed RDE corresponding to the n=5 resonance, and the associated power spectrum of the SXR line of sight  $I_{048}$  are shown in figure 5(c). The RDE envelope calculated

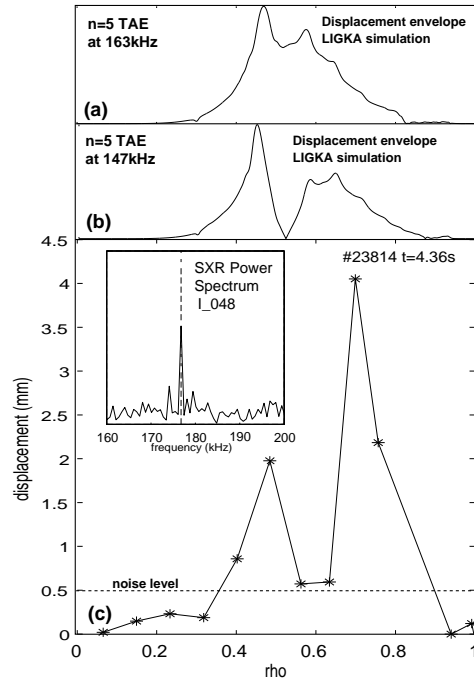


**Figure 3.** AUG discharge 23814: Even  $n=5$  TAE electrostatic potential eigenfunction (LIGKA)  $f=147\text{kHz}$  (plasma rest frame) at 4.36s. With experimentally derived density and safety factor profiles used in the simulation. The  $q$ -profile was generated by a CLISTE equilibrium reconstruction [14] constrained by magnetic measurements and the  $q = 1$  surface radius identified from SXR data.

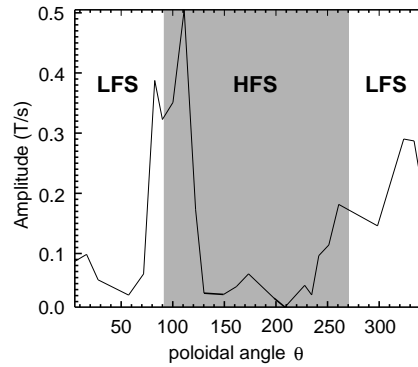


**Figure 4.** AUG discharge 23814: Even  $n=5$  TAE electrostatic potential eigenfunction (LIGKA)  $f=163\text{kHz}$  (plasma rest frame) at 4.36s.

from the SXR data has 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 shown in figure 5 (b) for the resonance at 147kHz, which exhibits the same radial structure and extent. In contrast the RDE envelope of the resonance at 163kHz, part (a), has only a shallow local minimum. Furthermore the amplitude distribution measured by a poloidal mirnov probe array in figure 6 shows the driven mode has an even character identified by the wide minimum centred on  $180^\circ$  on the high-field-side[6] consistent with the even character of the eigenfunctions shown in figure 3, and a fractional amplitude of  $\tilde{B}/B \simeq 10^{-6}$ , which will not significantly perturb the plasma[13]. We conclude that the resonance at 147kHz is the observed  $n=5$  mode and confirms it to be an even global  $n=5$  TAE. The location



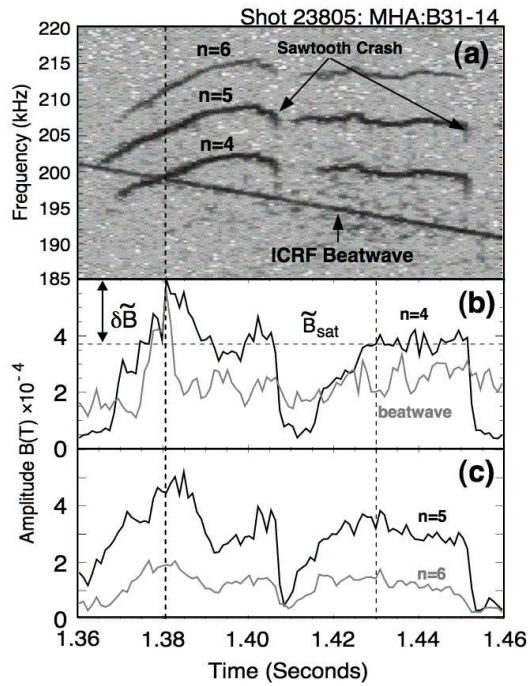
**Figure 5.** AUG discharge 23814: RDE envelope predicted by LIGKA for the  $n=5$  TAE at 147kHz (a) and 163kHz (b). (c) RDE envelope calculated from SXR data at  $t=4.36$ s. Corresponding power spectrum (insert), showing excited mode at 177kHz.



**Figure 6.** AUG discharge 23814: Poloidal amplitude distribution from mirnov probe array for the  $n=5$  TAE at  $t=4.36$ s.

and extent of this mode is similar to global fast ion excited TAEs studied at ASDEX Upgrade[6][15][16]. In particular, fast ion excited TAEs whose eigenfunctions change in sign have been measured at ASDEX Upgrade[16].

Through comparison of the simulated and reconstructed TAE's RDE, the position and safety factor value (the latter prescribed by theory[17]) of the gap in the Alfvén continuum from which the TAE originates can be extracted. Thus each TAE excited by an ICRH beatwave provides a point of safety factor profile information with which the plasma equilibrium reconstruction can be directly constrained[14].



**Figure 7.** AUG discharge 23805: (a) Spectrogram of the mirnov coil signal B31-14. (b) Increase  $\delta\tilde{B}$  of the tracked n=4 TAE's amplitude above its saturated amplitude  $\tilde{B}_{sat}$  and the tracked amplitude of the beatwave. (c) tracked amplitudes of the n=5,6 TAEs.

In discharge #23805, the plasma parameters were similar to those in #23814 with the exception of a lower  $P_{rad} = 2.5\text{MW}$  as a result of a lower high-Z impurity content. This produced a fast ion drive sufficient to overcome damping and excite TAEs. In figure 7 (a) the fast ion excited n=4 TAE frequency coincides with the ICRH beatwave frequency at 1.38s,  $f_{bw} = f_{TAE}^{lab}$ . In parts (b,c) the tracked amplitudes of the n=4,5,6 TAEs and beatwave are shown. Furthermore, in figure 7 the frequently observed periodic stabilising effect of sawtooth crashes on TAEs excited by fast ions alone can also be seen. From the (n=4, f=200kHz), (n=5, f=206kHz) and (n=6, f=211kHz) TAEs, the plasma rest frame frequency  $f_{TAE}$  of these modes and the plasma rotation frequency are found (through linear extrapolation in the toroidal mode number n) to be 178kHz and 5kHz, respectively. At the coincidence, the mode's phase, as measured from a toroidally arranged set of mirnov coils, is still 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  $\delta\tilde{B} = 2.3 \times 10^{-4}\text{T}$  above the TAE's saturated amplitude  $\tilde{B}_{sat} = 3.8 \pm 0.8 \times 10^{-4}\text{T}$ , 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 solely due to the ICRH accelerated fast ion drive as identified for times when  $f_{bw}$  and  $f_{TAE}$  do not coincide and the mode has recovered from the effect of the sawtooth crash. At the same time point, it can be seen in figure 7 (c) that 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. Thus the  $n=5,6$  TAEs exhibit a behaviour similar to the  $n=4$  TAE up until 1.43s after which they decouple and behave independently. Therefore an ICRH beatwave can also be used to influence the stability of fast ion excited TAEs, such that their effect on the fast ion population can be studied.

In conclusion, this letter reports the first successful reconstruction of the radial displacement eigenfunction structure and subsequent identification of an ICRH beatwave driven 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.

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