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A characterisation of Alfvénic instabilities and use in the reconstruction of current density profiles at ASDEX Upgrade

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Introduction

In a tokamak plasma, knowledge of the toroidal plasma current profile is essential for the calculation of plasma equilibrium and plasma stability against MHD phenomena. To this end, the study of the behavior and effects of MHD instabilities can reveal considerable information about the current profile within the plasma. In a magnetised plasma, Alfvén Eigenmodes with a characteristic velocity $V_A = B/\sqrt{\mu_0 \rho}$ (magnetic field B, density profile ρ), can be excited through Inverse Landau Damping of resonant fast ions [2]. Toroidicity in a tokamak leads to a modification of the Alfvén spectrum, in that shear Alfvén waves with adjacent poloidal mode numbers (m,n) and (m+1,n) can couple toroidally resulting in the formation of gaps. Within these gapes, modes with well defined toroidal structure, so called TAE can be excited. This in turn allows these modes to grow and via Landau Damping alter the orbits of trapped fast ions leading to the premature loss of these ions. These TAE induced losses are seen in the new fast ion loss detector at ASDEX Upgrade. Additionally, recent experiments have demonstrated the ability of fixed and swept frequency ICRF beatwaves to amplify MHD instabilities. This has the potential to provide a passive tool to excite MHD instabilities, and in particular TAE at regular time intervals for each discharge that uses ICRF power. Using various diagnostics, such as SXR, Mirnov, ECE and reflectometry, all MHD instabilities present can be analysed to provide information to constrain the q-profile reconstruction [5].

Toroidal Alfvén Eigenmodes at ASDEX Upgrade

In a tokamak, a TAE has a well defined toroidal mode number n and frequency f, but since it is formed as a result of toroidal coupling of two shear Alfvén waves it can not be identified with a unique poloidal mode number m. In spite of this one can define a 2D displacement eigenfunction [1]. At the crossing point of the Alfvén spectra of the (m,n) and (m+1,n) shear waves, a gap TAE frequency is defined as $f_{TAE} = V_A/2q_{gap}R$, where $q_{gap} = (m+1/2)/n$ and R is the major radius coordinate of the crossing point. As a result of the toroidal plasma rotation, the frequency of TAE measured in the lab frame are doppler shifted and thus is possible to estimate the plasma rotation at the resonance surface of the TAE [7]. Once this f_{TAE} has been calculated, one can estimate the position of this gap using available density and q profiles. If kinetic effects are in fact large, this analysis becomes less reliable because the actual frequencies of individual TAE within the same gap are modified, leading to larger frequency differences between TAE with adjacent toroidal mode numbers than can be attributed to plasma rotation alone [1]. Since TAE are very sensitive to major bulk plasma parameters through the strong dependance of f_{TAE} on the toroidal field B_{tor}, density profile ρ and the q-profile, it is possible to directly manipulate the behavior of TAE. On the other hand one can also infer the dynamic behavior of the relevant bulk plasma parameters by observing the behavior of TAE [4],[5].

TAE driven by ICRH fast particles

Many experiments have demonstrated the ability of ICRF accelerated fast ions to destabilise TAE and the relevant theory has also been developed to put this driving mechanism on a strong physics footing. The important resonance condition is $f_{TAE} = pf_{bounce} + lf_{tor.precession}$, where f_{bounce} is the bounce frequency of trapped ions, $f_{tor.precession}$ is the toroidal precessions frequency with p and l being integers [2]. For TAE pf_{bounce} is the dominant term, whereas for Fishbones the integer multiple of the toroidal precession frequency is the important term. In the discharge shown in figure 1, we see three strong TAE with n=[4,5,6] and a weaker n=3. These TAE are among the usual numbers seen on ASDEX Upgrade. The complete range of potential TAE are n=[3,4,5,6,7], with n=[4,5] normally being the most unstable [1]. From the doppler shift calculated from the difference in frequency between successive TAE is approximatively 5kHz. Comparing this to the 5.3kHz rotational frequency of a (1,1) mode present at the same time, we see that at this time it is a fair approximation of the plasma rotation. When a strong sawtooth crash occurs, one may see a complete stabilisation of the TAE as a result of a reduction in available drive due to the expulsion of fast ions [1]. Here the damping rate $\gamma = \Delta f/f$ for the n=4 TAE was estimated to be 0.5%. In this discharge, a density ramp was performed to demonstrate the characteristic Alfvén dependance on density. This is seen in the close correlation between the doppler corrected frequency and the predicted gap frequency from density and q profiles. The density ramp also provides us with two further piece of information, which are a power/density threshold pair $(5.7MW, 5.1e19m^{-3})$ and in this case, at 5.55s the n=5 is the last TAE to be stabilised by increasing density. We see TAE of different n stabilising at different times. This indicates that the damping related to the decrease in β_{fast} by the increasing density is n-dependant and centered on n=5 for ASDEX Upgrade.

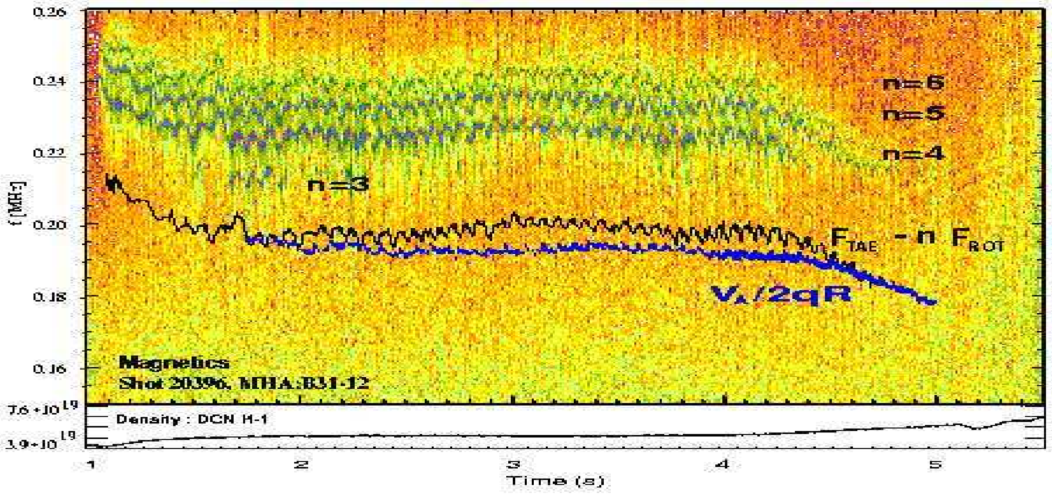

Figure 1: Discharge #20396 Comparison of Doppler Corrected TAE frequency and Gap TAE frequency, (B_T=2.43T, I_p=0.9MA, n_e *ramp* : $2.8e19m^{-3} \rightarrow 6.5e19m^{-3}$, *Power Ramp* : $2.6MW$ *at* $1.0s \rightarrow 5.1MW$ @ $1.9s\ P_{ICRFc} = 5.1MW\ 1.9s \rightarrow 6.0s$).

TAE induced Fast ion losses

Through the inverse Landau damping energy transfer mechanism, TAE can be destabilised via the resonant interaction with ICRF accelerated ions [2]. In the reverse case the orbits of confined trapped fast ions in phase space can be altered sufficiently to put them into lossy orbits. In figure 2, we see that in this shot we have several TAE present with toroidal mode numbers n=4,5,6 at 1.4s and n=4,5 at the later time period of 1.8s. In the lower figure we also see the expected accompanying fast ion losses in the fast ion loss detector. The energies and pitch angle of these losses are 500keV and 70^0 respectively [3]. This clearly identifies these losses as ions accelerated ICRF. The NBI had been turned off at 1.2s and the maximum energy provided by the NBI system is 100keV. The pitch angle identifies these losses as trapped ions which is consistent with the resonance condition. The TAE seen in this discharge vary significantly over this 0.8s time window.The density is ramping up until 1.6s and ramping down thereafter. This decreases the local Aflvén frequency up until 1.6s and decreases the TAE driving source. After that the reverse happens. The most dramatic effect is that we see the losses disappear during the ELM-free H-Mode phases. The cause of this apparent loss of signal has not been uniquely identified, although several possible causes are being examined [3].

MHD Instabilities excited by ICRF Beatwaves

At ASDEX Upgrade, two pairs of ICRF antennae launch electromagnetic waves with two different frequencies f_1 and f_2. These waves then interact non-linearly via the plasma to form beatwave in the plasma of frequency $\Delta f = f_1 - f_2$. Additionally, it is not clear what effect the inhomogeneity of the RF fields has and which fields (near- or far-antenna fields) are important for beatwave generation. Each antenna is toroidally shifted with respect to each of the other

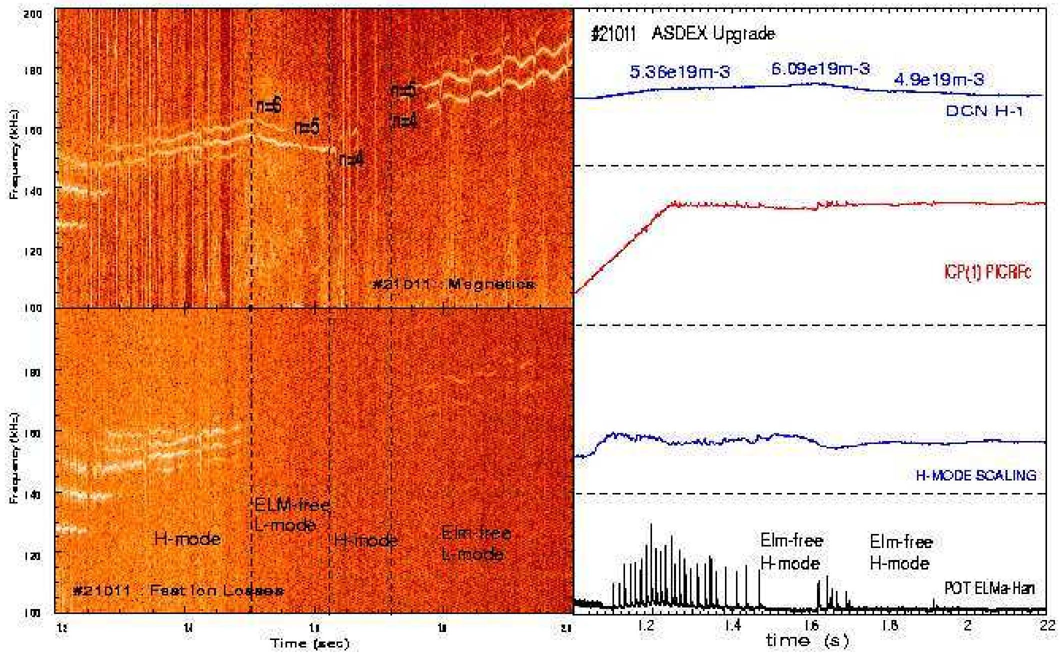

Figure 2: Discharge #21011 TAE fast ion losses

antennae. This leads to a beatwave with a complex, radial and toroidal amplitude distribution. This tool provides a selective excitation mechanism which complements the broadband excitation provided by the ICRF accelerated ions. One example of the results thus far are presented in figure 3. Here one can see the spectrogram of the difference of the signals from two coils situated on the high field side midplane and low field side midplane positions. This analysis is designed to enhance coherent signals and to suppress those that are not.

In figure 3, we clearly see well defined responses in the magnetics. We see that the beatwave enhances what appears to be broadband turbulence seen between 150kHz and 100 kHz. It is believed that these are TAE localised using SXR at rho poloidal = 0.5. In similar discharges resonances are also seen at lower frequencies and these are thought to be edge localised TAE excited by drift Alfvén turbulence[6]. It was determined from reflectometry that these modes are edge localised. In order to fine tune this tool to excite all possible TAE, we must further understand how the beatwave power is distributed relative to the Alfvén resonances in the plasma.

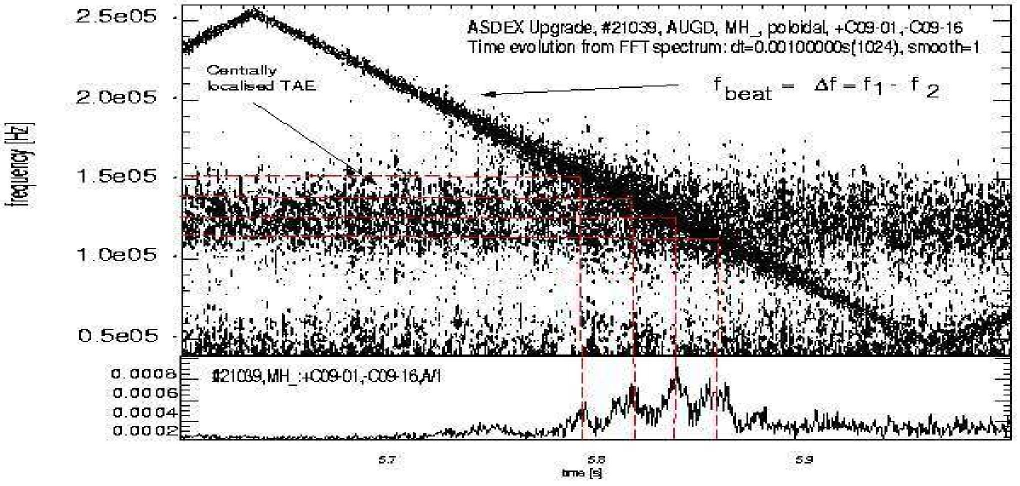

Figure 3: Discharge #21039 Observed ICRF Beatwave excitation of central TAE

Current Profile Reconstructions using TAE and other MHD Instabilities using CLISTE

Once an MHD instability has been identified and localised using a combination of the Mirnov, SXR, ECE and Reflectometry diagnostics, this information can then be used to constrain the q-profile and hence the current density profile during reconstruction [4],[5]. In a single discharge it is possible to have within a sufficiently small time interval, the (1,1) Sawtooth instability, (3,2) and (2,1) NTM coexisting. These three MHD instabilities provided three additional points of q-profile information. Figure 4, compares the cases of reconstructions done with and without extra q profile information. In this example, one can see from the reconstruction performed using multiple extra q points simultaneously, a large difference from the q=1.5 surface inwards. Similarly, the simultaneous inclusion of TAE information in addition to that supplied by low frequency MHD will further increase the quality of equilibrium reconstructions. Thus TAE will be of particular use in current density reconstructions because in practice, TAE in the same gap are not all in same position nor do they have the same frequency. So not only does one have a radial point of each eigenfunction, one has multiple points very close together. This adds a constraint on dq/dr in an important region of the profile. Therefore TAE will be invaluable for current profile reconstructions.

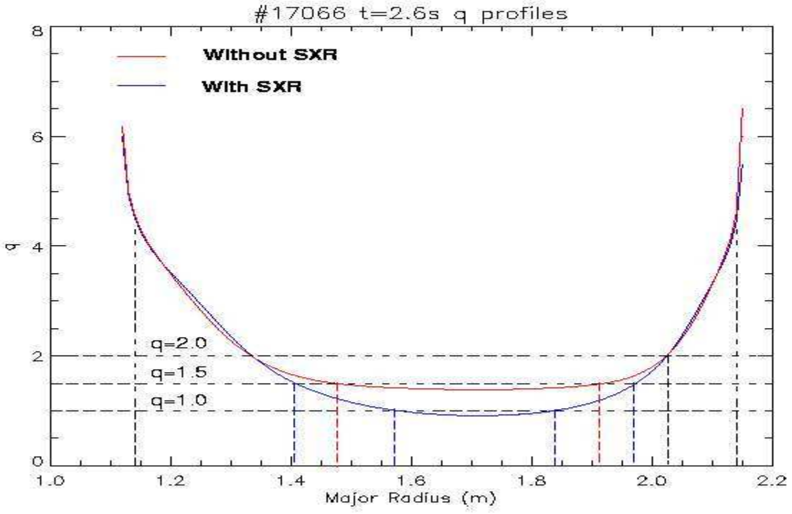

Figure 4: Discharge #17066 q-profile reconstrunction using MHD instabilities

Conclusions

TAE can be driven unstable by ICRF accelerated ions in ASDEX Upgrade using $P_{ICRF} > 4 - 5.7$ MW for densities up to $5.5e^{19}m^{-3}$. The most unstable toroidal mode numbers seen on ASDEX Upgrade are n=[3,4,5,6,7] with a density related damping clearly dependent on the toroidal mode number n of the TAE. In addition to this, equilibrium reconstructions simultaneously using multiple q points from low-frequency MHD have proved very sucessfull. Similarly, the simultaneous inclusion of TAE information in addition to that supplied by low frequency MHD will further increase the quality of equilibrium reconstructions.

Recent experiments have shown that ICRF Beatwaves are able to amplify centrally and edge localised TAE. In order to fully exploit and refine this tool, a model of the Beatwave power distribution in the plasma is required, to fully resolve the observed complexity of the plasma responses.

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