Destabilisation of TAE modes using ICRH in ASDEX Upgrade

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Abstract. In ASDEX Upgrade, toroidicity induced Alfvén eigenmodes (TAEs) are destabilised by ICRH in conventional and advanced scenarios, at low density. Most unstable TAEs have toroidal modes numbers (n=3,4,5,6) and experiments with reversed current and magnetic field showed that the TAE propagate in the current direction. On one hand, the analysis of the unstable TAE in ASDEX Upgrade shows that the data is consistent with the results from previous studies performed in other tokamaks. In particular, the measured TAE frequency, in the range (150-200kHz), is consistent with theoretical TAE frequency calculated for the parameters of the discharges performed in these experiments. On the other hand, some interesting new features have also been observed in the ASDEX Upgrade data. TAE (n=-1) was observed, which propagates in the opposite direction to the plasma current. It was also concluded that plasma rotation is insufficient to explain the experimentally observed frequency differences between two adjacent toroidal mode numbers. The measured relative fluctuation amplitude of the TAE eigenfunction in the soft X-rays channels increases towards the plasma edge. These results are consistent with the ideal MHD calculations and show that the TAE are of a global nature and not core localised TAE modes. These results are particularly important, because the radial extent of AE is a key factor in the redistribution of the energetic ions in the presence of unstable TAE. In advanced Tokamak scenarious, no evidence of Alfvén Cascades was observed in experiments with ICRH minority heating in the early phase of the discharge. The effect of Electron Cyclotron Current Drive (ECCD) on the TAE amplitude was studied by applying different levels of ECCD in similar plasma configurations, with equivalent ICRH power. It was observed that ECCD has a slight destabilizing effect on the TAE.

1. Introduction

The understanding of plasma instabilities is of great importance for the optimization of the design and future operation of a tokamak fusion reactor [1]. Alfvén instabilities are particularly important due to the fact that the charged fusion products (α particles) which provide the plasma heating have a birth velocity $v_\alpha=1.3\text{x}10^7 ms^{-1}$, larger than the Alfvén velocity $v_A=B/\sqrt{\rho}\approx 10^7 ms^{-1}$. Unstable Alfvén Eigenmodes (AE) [2,3,4] can cause the redistribution/loss of fast ions, leading to a reduction of heating efficiency and ejected alpha particles can also damage the first wall components of a reactor.

In present tokamak experiments, the destabilisation of AE can be studied using super-Alfvénic ions generated by auxiliary heating systems such as neutral beam injection (NBI) and Ion Cyclotron Resonant Heating (ICRH). The study of AE destabilization by energetic ions produced by auxiliary heating, such as ICRH and NBI, is a valuable tool in understanding the physics issues related to Alfvén instabilities. These experiments offer the possibility of validating the models used in the extrapolation to reactor conditions. Numerous studies have been performed, with various levels of detail, using data from various tokamaks such as [5], JT60-U [6], DIII-D [7] and JET [8,9,10,11,12]

2. TAE Instability in ASDEX Upgrade

In a tokamak, an instability can be characterised by the amplitude, frequency and mode structure as given by $\xi = A\, \zeta(r,\theta)\, e^{i(2\pi f t + n\phi)}$, where A is the amplitude, $\zeta(r,\theta)$ is the 2-dimensional plasma displacement, f the frequency and n the toroidal mode number. In ASDEX Upgrade, TAE are observed in the frequency range of $f_{TAE}\approx$150-200kHz, consistent with the TAE frequency $f_{TAE}=V_A/(4\pi q R_0)$ for the magnetic field of B_T=2T, electron density of n_e=3-5x10^{19}m^{-3} and major radius of R_0=1.65m. Most unstable TAEs have toroidal mode numbers (n=3,4,5,6) and experiments with reversed current and magnetic field showed that the TAE propagate in the co-current direction, as shown in figure 1, i.e. in the ion diamagnetic drift direction, confirming that these modes are destabilised by the ICRH produced energetic ions.

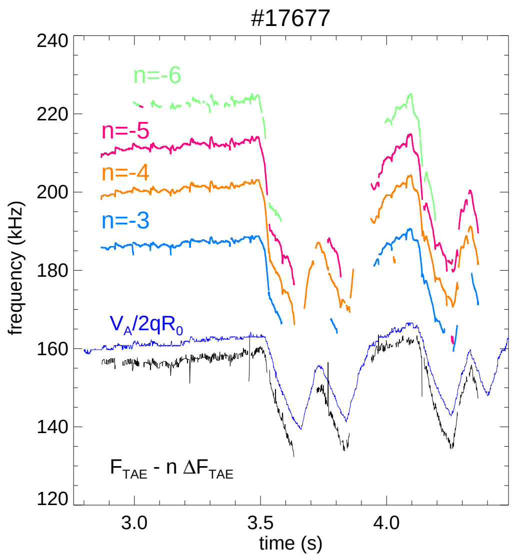

Figure 1 Frequency of the TAE modes observed with different toroidal mode numbers as a function of time, compared with $f_0=f_{TAE}-n\ (f_{(n)}+f_{(n-1)})$ for n=4 and the Alfvén frequency at q=1.5, for a reversed magnetic field configuration.

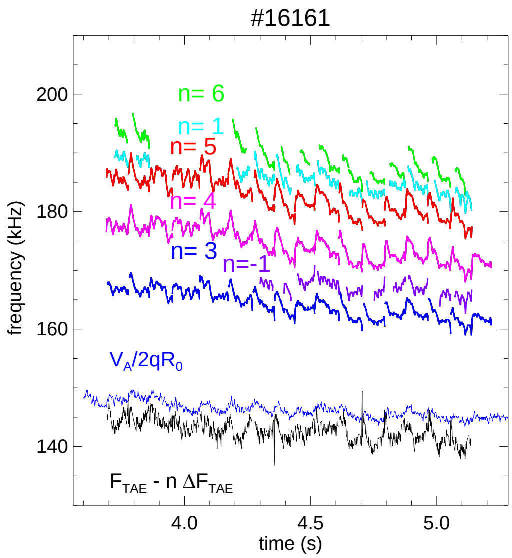

Figure 2 Frequency of the TAE modes observed with different toroidal mode numbers as a function of time, compared with $f_0=f_{TAE}-n\ (f_{(n)}+f_{(n-1)})$ for n=4 and the Alfvén frequency at q=1.5, for a normal magnetic field configuration.

In discharge #16161, a n=-1 is also observed, which propagates in the opposite direction to the other 5 modes (n=1,3,4,5,6) as seen in figure 2. The observed amplitude of the n=-1 and n=1 modes is around δB~0.1 T/s an order of magnitude smaller than the n=3,4,5 modes which is around δB~1 T/s. TAE modes propagating in the direction opposite to the ion diamagnetic drift direction are seen in ASDEX Upgrade, if the ICRH power exceeds P_{ICRH}>5MW in conventional scenarios. It is possible that at these levels of ICRH power, particles with large energy and orbit widths are generated. Large orbits leads to non-standard distribution functions, leading to inverted gradients in energy and toroidal canonical momentum. Therefore, TAE propagating in both directions can be destabilised.

3. Effect of plasma toroidal rotation on the TAE frequency

A dedicated set of experiments were performed in order to study the effect of toroidal plasma rotation on the TAE frequency. The Doppler correction to the TAE frequency due to the plasma toroidal rotation (f_{ROT}) $f_{LAB}=f_{TAE}+n\ f_{ROT}$ was analysed in plasmas with the rotation measured using the Charge Exchange Spectroscopy diagnostic (CXS) and compared with the rotation of other MHD modes such as the sawtooth instability n=1 precursors. This was achieved by injecting a short (50ms) NBI heating pulse (NBI blip) during the ICRH heating phase with unstable TAE. The use of NBI heating allows the measurement of rotation using CXS, but changes the plasma toroidal rotation via the injection of toroidal momentum into the plasma.

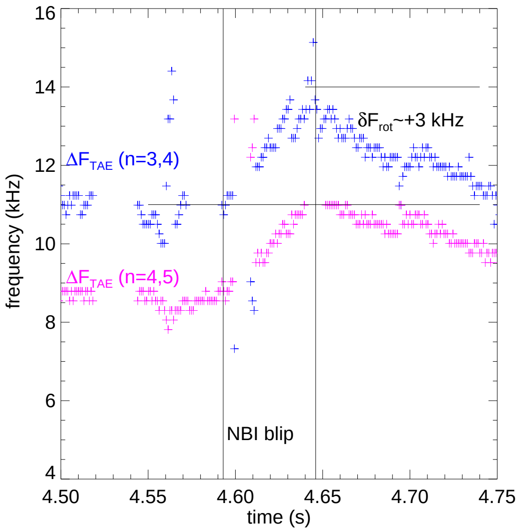

Figure 3 Frequency differences for TAE (n=3 n=4) and (n=4, n=5) as a function of time for discharge #17758 performed with forward magnetic field and current direction. During the NBI blip ΔF_{TAE} n=3,4 and ΔF_{TAE} n=4,5 increase by around 3 kHz, consistent with an increase of the plasma rotation of around ΔV_{rot}=30km/s.

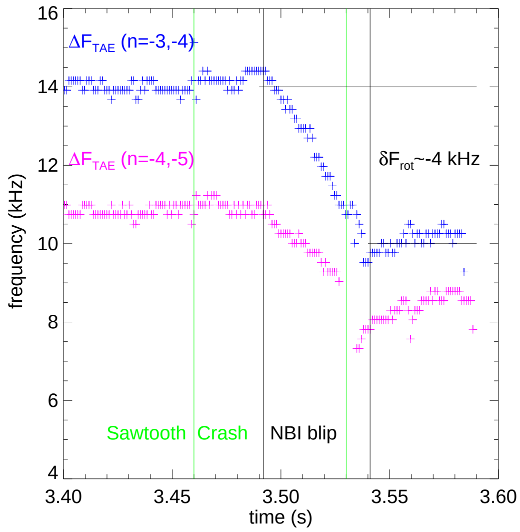

Figure 4 Frequency differences for TAE (n=3 n=,4) and (n=4, n=5) as a function of time for discharge #17677 performed with reversed magnetic field and current direction. During the NBI blip ΔF_{TAE} n=3,4 and ΔF_{TAE} n=4,5 decrease by around 4 kHz, consistent with a change in the plasma rotation of around ΔV_{rot}=40km/s

In the normal magnetic field and current configuration, the frequency differences between the n=3, n=4 TAE (ΔF_{TAE} n=3,4) and n=4, n=5 TAE (ΔF_{TAE} n=4,5) increase by around 3 kHz during the NBI blip, as shown in figure 3. This is consistent with an increase of the plasma rotation of around ΔV_{rot}=30km/s. In the reversed magnetic field and current configuration, the frequency differences between the n=3, n=4 TAE (ΔF_{TAE} n=3,4) and n=4, n=5 TAE (ΔF_{TAE} n=4,5) decrease by around 4 kHz during the NBI blip, consistent with a change of the plasma rotation of around ΔV_{rot}=40km/s, as shown in figure 4. During the NBI blip, the ICRH induced rotation is balanced by the low power NBI blip and the bulk toroidal rotation transiently crosses 0 kHz. However, significant TAE frequency differences of around Δf_{TAE}

=8-12 kHz were observed. The precise origin of the differences between the frequency of two adjacent toroidal mode numbers Δf_{TAE} was analysed in detail. It was concluded that plasma rotation f_{rot}<2kHz, diamagnetic effects f<0.5kHz and profiles effects f<2kHz are insufficient to explain the experimentally observed frequency differences between two adjacent toroidal mode numbers TAE (Δf_{TAE}~7-8kHz) [13]. It is possible that kinetic effects also significantly modify the TAE frequency in the presence of a large fraction of energetic ions, providing a possible explanation for the observed discrepancy.

4. Radial mode structure

In ASDEX Upgrade, the radial extent of the TAE eigenfunction can be obtained by combining the information from magnetic sensors "Mirnov probes", microwave reflectometer [14,15] and soft X-rays emission [16]. The magnetic data provides information on the vacuum magnetic field perturbation outside the plasma. The reflectometer gives information on the perturbation in several radial positions, corresponding to the fixed frequency microwave beam cut-off layers. For the discharges used in these experiments, 4 channels were available on the high field side and 4 channels on the low field side. However, due to the limitation of the homodyne detection system used in these channels, only qualitative amplitude information could be obtained. Therefore, most information is obtained from the horizontal soft X-ray camera C, the only camera installed with fast diodes capable of detecting the high frequency TAE perturbations.

The MHD model shows the existence of two n=3 TAE modes in this plasma configuration with distinct radial mode structures. The MISHKA code calculated eigenfunctions of the usual global n=3 TAE, which cross several continuum gaps and the core localised n=3 TAE, located in a single continuum gap [17,18]. Both types of mode structures are compared with the measured soft X-rays emissivity fluctuations. The comparison between the core localised eigenfunction and the measured soft X-rays emissivity fluctuations is shown in figure 5. It is shown that agreement is reasonable for the most inner channels 18-25 probing the plasma core in the region $\sqrt{\Psi/\Psi_{edge}} < 0.2$, where Ψ represent the poloidal magnetic flux. However, in the region $0.2 < \sqrt{\Psi/\Psi_{edge}} < 0.5$ crossed by the channels 26-30 the agreement is poor. On the other hand, comparison between the global eigenfunction and the measured soft X-rays emissivity fluctuations (figure 6), shows good agreement for all channels 16-30 probing the region $\sqrt{\Psi/\Psi_{edge}} < 0.5$. Therefore, it can be concluded that the modes observed are global TAE and not core localised TAE modes. The maximum amplitude of the perturbation in the region covered by the soft X-rays camera $\sqrt{\Psi/\Psi_{edge}} < 0.5$ is estimated to be 0.39mm, by fitting the calculated perturbation amplitude to the experimental data, corresponding to a magnetic perturbation of $\frac{\delta B}{B} = \frac{\xi}{2qR_0} \approx 10^{-4}$ in the core [13].

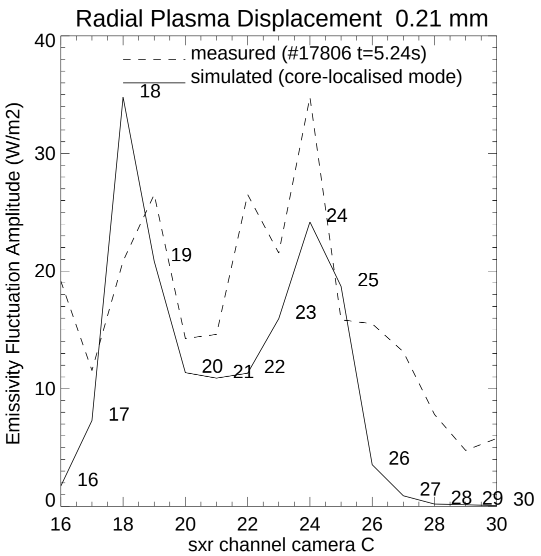

Figure 5 The comparison between the n=3 core localised TAE eigenfunction and the measured soft X-rays emissivity fluctuations. The maximum amplitude of the perturbation in the region covered by the soft X-rays camera $\sqrt{\psi/\psi_{edge}} < 0.5$ *is 0.21 mm.*

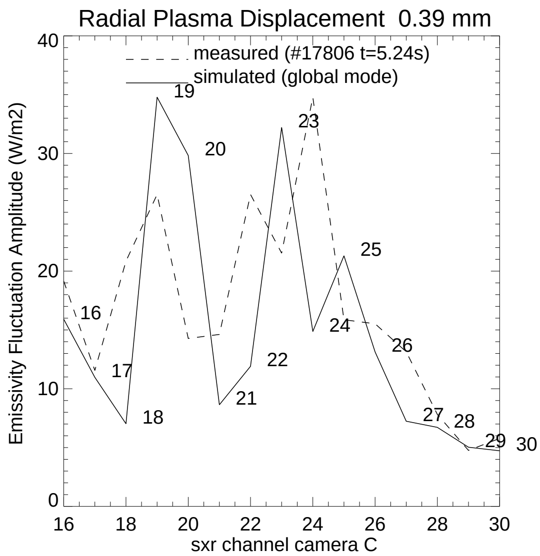

Figure 6 The comparison between the global n=3 TAE eigenfunction and the measured soft X-rays emissivity fluctuations. The maximum amplitude of the perturbation in the region covered by the soft X-rays camera is 0.39mm.

5. Alfvén Eigenmodes (AE) in advanced scenarios

A set of dedicated experiments were carried out in order to study the AE spectrum in advanced tokamak scenarios. AE were destabilized by applying ICRH minority heating (4 MW) in the early phase of the discharge (#17808, Bt=2.4 T, Ip=1.0 MA). Early AE activity (t<1.0 s) is consistent with flat or slightly inverted q profiles with small reversed shear, as shown in figure 7. During the NBI heating phase (t>1.0 s), the TAE activity is consistent with a monotonic q profile and no evidence of Alfvén Cascades [19,20] was observed in this experiments.

On the other hand, evidence of Alfvén Cascades was observed after a heavy impurity accumulation event in the core, in discharge (#17611, Bt=2.0 T, Ip=0.8 MA), as shown in figure 8. This observation is consistent with a reversed shear profile being caused by hollow temperature profiles due to strong core radiation from core impurities. This observation was made in a reversed current and magnetic field configuration. Therefore, the measured AE toroidal mode numbers are negative, as shown in figure 8.

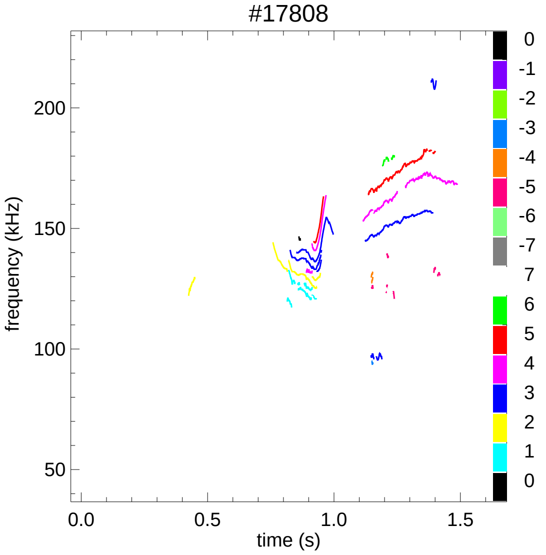

Figure 7 Frequency of the AE as a function of time with different toroidal mode numbers for discharge (#17808) with early (t<1.0s) ICRH minority heating. No evidence of Alfvén Cascades were observed in these experiments.

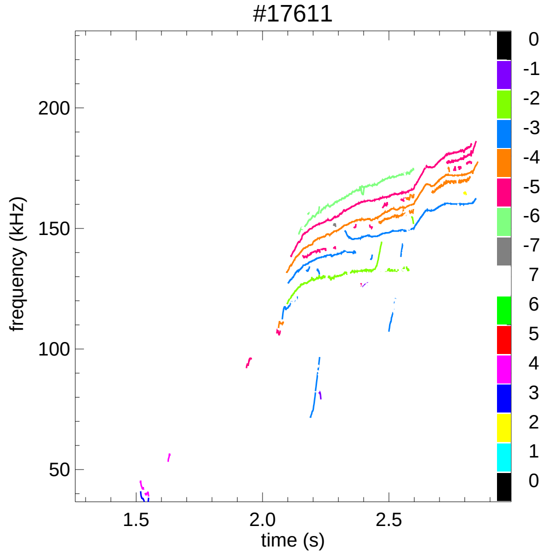

Figure 8 Frequency of the AE as a function of time with different toroidal mode numbers for discharge (#17611). Alfvén Cascades were observed after a heavy impurity accumulation event in the core (t=2.0s).

6. Effect of Electron Cyclotron Current Drive (ECCD) on Alfvén Eigenmodes

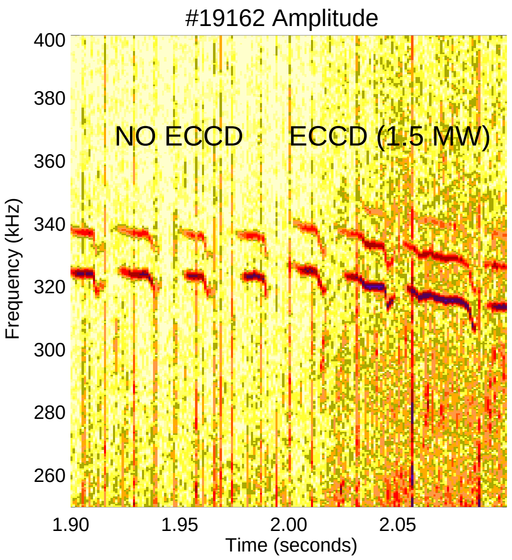

Figure 9 Frequency of the AE as a function of time showing effect of Electron Cyclotron Current Drive (ECCD) on the TAE amplitude

The effect of Electron Cyclotron Current Drive (ECCD) on the TAE amplitude was studied by applying different levels of ECCD in similar plasma configurations, with equivalent ICRH power. In discharge #19162 (Bt=2.0 T and Ip=0.8 MA), a constant level of ICRH power (5MW) was applied and 1.5 MW of ECCD was switch on at t=2.0s, as shown in figure 9. Without ECCD, two TAE modes are observed with frequencies around (300-350 kHz) and the TAE are frequently interrupted by sawteeth. By applying 1.5 MW of ECCD the amplitude of the TAE increase, as measured by the "Mirnov" probes and the TAE survive most of the sawtooth period. A third mode can also be seen during the ECCD phase. Therefore, ECCD has a slight destabilizing effect on the TAE. This could be caused by a different TAE damping, due to changes in the q profile, but more detailed modeling is required to verify this assumption.

7. Conclusions

TAE are destabilised by ICRH in ASDEX Upgrade for P_{ICRH} > 2-3 MW in conventional and advanced scenarios, at low density n_e=3-5x10^{19}m^{-3}. Most unstable TAEs have toroidal modes numbers (n=3,4,5,6) and experiments with reversed current (I_P) and magnetic field (B_T) showed that the TAE propagate in the current direction.

The measured TAE frequency, in the range ($f_{TAE}\approx$150-200kHz), is consistent with theoretical TAE frequency calculated for the parameters of the discharges performed in these experiments.

The precise origin of the differences between the frequency of two adjacent toroidal mode numbers Δf_{TAE} was analysed in detail. It was concluded that plasma rotation f_{rot}<2kHz, diamagnetic effects f<0.5kHz and profiles effects f<2kHz are insufficient to explain the experimentally observed frequency differences between two adjacent toroidal mode numbers TAE (Δf_{TAE}~7-8kHz). It is possible that kinetic effects also significantly modify the TAE frequency in the presence of a large fraction of energetic ions, providing a possible explanation for the observed discrepancy.

The measured relative fluctuation amplitude of the TAE eigenfunction in the soft X-rays channels increases towards the plasma edge. These results show that the TAE are of a global nature and not core localised TAE modes.

No evidence of Alfvén Cascades was observed in experiments with ICRH minority heating in the early phase of the discharge. On the other hand, evidence of Alfvén Cascades was observed after a heavy impurity accumulation event in the core.

The effect of Electron Cyclotron Current Drive (ECCD) on the TAE amplitude was studied by applying different levels of ECCD in similar plasma configurations, with equivalent ICRH power. It was observed that ECCD has a slight destabilizing effect on the TAE.

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