# Observation of TAE-modes in ohmically heated plasmas by drift wave excitation

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The common understanding about the excitation of toroidicity-induced Alfvén Eigenmodes (TAE-modes) requires fast particles in the range of the Alfvén speed $v_A = B/\sqrt{\mu_0 n_i m_i}$ or in tokamaks one third of the Alfvén speed through sideband excitation.

Recently, in ASDEX Upgrade, TAE-modes have also been observed in purely ohmically heated discharges, where only fast particles from the Maxwellian distribution are present, which are not able to drive these modes unstable. Their frequencies scale with $f_{TAE} = \frac{1}{2\pi}\frac{v_A(r)}{2q(r)R}$, and they are located at the $q \approx 2.6$ surface. They can be observed on Mirnov and soft-X-ray measurements. A new excitation mechanism by coupling of the electromagnetic part of the drift Alfvén turbulence at the cold plasma edge to the ordinary Alfvén wave spectrum could explain their appearance.

**Model of TAE-modes** In the cylindrical large aspect ratio approximation two adjacent branches of the localized continuum shear Alfvén waves with the dispersion relation $\omega_A = v_A(r)\left|k_{\|}\right|$, $k_{\|} = (m-nq)/(qR)$ have a crossing point at the $q = (2m+1)/(2n)$ surface at which the modes with subsequent poloidal mode numbers $m$ and $m' = m \pm 1$ have degenerated energy states. Considering the toroidicity with a realistic aspect ratio of tokamaks, e.g. $R/a \approx 3.3$ for ASDEX Upgrade, the poloidal variation of the toroidal field $B_t$ causes a coupling of the two adjacent branches and two standing waves are created. The degeneracy of the branches is resolved by these standing waves and at the corresponding frequency a gap is formed in which no radially localized continuum Alfvén wave can exist anymore. Within this gap a TAE-mode can exist with approximately the frequency of the former crossing point $f_{TAE} = \frac{1}{2\pi}\frac{v_A(q_{GAP})}{2q_{GAP}R}$.

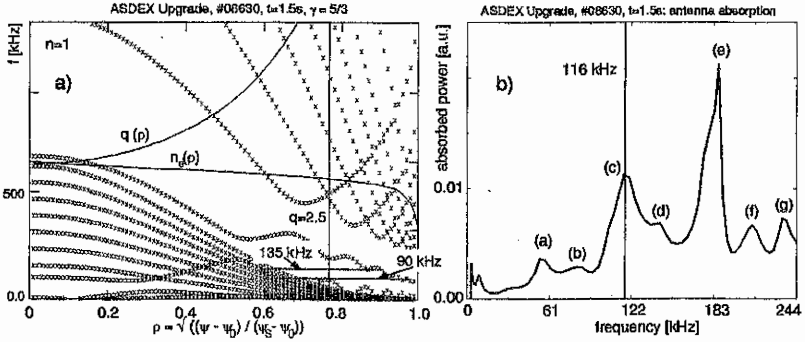

Figure 1: *a: Dispersion relations for continuum Alfvén waves for $n = 1$ calculated by CASTOR. b: Antenna absorption spectrum for the presented dispersion relations.*

To get an better description of TAE-modes, e.g. their exact frequencies and full radial structure, a toroidal resistive MHD-code like CASTOR [1] has to be used. This code solves the linearized MHD equations in the full toroidal geometry and calculates the continuum Alfvén wave branches and in addition the frequencies and structures of the TAE-modes within the continuum gaps. The resulting dispersion relations are shown in Fig. 1a. The exact frequencies of the modes are determined by an extension of CASTOR in which the power absorbed by the plasma in response to a wave injected by external antennas is calculated as a function of frequency [2] (Fig. 1b). The maximum of the absorbed power gives the exact central frequencies of the TAE-modes at which the radial structure can then be calculated. The resulting eigenfunctions have a global structure and are spread over the minor plasma radius until they cross an Alfvén continuum branch. Their maximum amplitude is still localized at the position of the former crossing point of the continuum Alfvén waves at $q_{GAP} = (2m+1)/(2n)$ with a frequency of $f_{TAE} = \frac{1}{2\pi}\frac{v_A(r)}{2q(r)R}$.

**Observation of TAE-modes in ohmic discharges** Recently, at ASDEX Upgrade, TAE-modes with their characteristic structure in the Fourier spectrum of the Mirnov coils have also been observed in purely ohmically heated discharges. A typical spectrum of a Mirnov coil mounted at the high field side of the torus is shown in Fig. 2a.

A clear difference to the modes observed in NBI-plasmas (burst-like behaviour with approximately 1 ms duration) is their continuous appearance throughout the entire discharge with a modulation of the envelope. The amplitude is about one order of magnitude smaller compared to the modes with NBI. These TAE-modes rotate in the electron diamagnetic drift direction.

If the observed modes were TAE-modes, the frequencies should depend mainly on the magnetic field $B \approx B_t$, the mass of the ions $m_i$ and the local density $n_e(q)$ on the relevant resonant surface. Comparing shots with different toroidal field $B_t$ and different ion species $m_i$, e.g. hydrogen and deuterium shows a clear dependence of the form $f \sim B_t/\sqrt{m_i}$. A strong density variation through different rates of gas puffing has been applied to check the dependence of the frequency on the local density on flux surfaces. The observed frequencies scale with density as $f \sim 1/\sqrt{n_e}$, as shown in Fig. 2b for measurements of the soft-X-ray diagnostic. Combining the results leads to $f \sim B/\sqrt{m_i n_e} \sim f_A$.

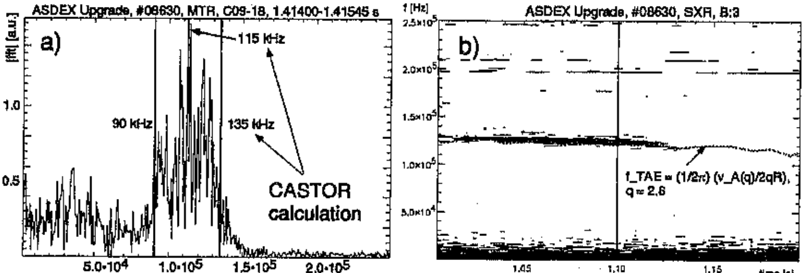

Figure 2: *a: A typical Fourier spectrum at the high field side of the torus. The broad spectrum has a significant amplitude in the range* $f = 85 - 140$ *kHz and reaches its maximum at* $f \approx 115$ *kHz. b: Dependence of the TAE-frequency upon the density as observed on the measurements from soft-X-ray.*

The remaining free parameter for calculating the location of the modes is the $q$-value $q_{GAP}$ of the modes which can be fitted to the measured frequency by the equation $f_{TAE} = \frac{1}{2\pi}\frac{v_A(q_{GAP})}{2q_{GAP}R} = \frac{1}{2\pi}\frac{B_t}{\sqrt{\mu_0 m_i n_e(q_{GAP})}}\frac{1}{2q_{GAP}R}$, where $Z_{eff} = 1$ has been assumed. The density $n_e(q_{GAP})$ is taken on the flux surface for which $q = q_{GAP}$ holds. A fit of the $q$-value gives a value close to the plasma edge of $q_{GAP} \approx 2.6$ at $\rho_{TAE} \approx 0.84$ in a discharge with $q_{95} = 5$ ($q$-value at 95% of the poloidal flux).

Measurements of the soft-X-ray camera system show a clear frequency peak with $f_{TAE} =$ 127 kHz at t = 1.0 s lying in the center of the observed multi peak structure of the Mirnov data for the corresponding time. The profiles reveals a $m = 0$ structure at this frequency. The maximum amplitudes are reached at the plasma edge consistently with the Mirnov data.

For these type of discharges for several time points a comparison with calculations of the resistive MHD-code CASTOR was done. The continuum spectrum for a typical time (#8630,t=1.5s) shows a gap in which TAE-modes can exist in the frequency range $f_{TAE,CASTOR} = 90 - 135$ kHz (Fig. 1). The spectrum of the absorbed power by external antenna excitation is shown in Fig. 1b. For the various peaks the resulting eigenfunctions have been analysed. All the eigenfunctions are radially peaked near the plasma center, where fast particles are normally present and are not excited. Only the frequency peaks (c) and (d) with $f \approx 115$ kHz show eigenfunctions, which are clearly peaked in the vicinity of the $q = 2.5$ surface. This frequencies are in perfect agreement with the observed frequencies and the mode location. For different times within the discharges the agreement also holds, besides the fact that different measured densities at the corresponding rational surface have to be applied to calculate the Alfvén frequencies.

At the L- to H- transition, the TAE-activity disappears or is strongly reduced in amplitude when the density fluctuation measured by reflectometry disappears (Fig. 3). During the H-mode the turbulence and also the TAE-modes reappear as bursts. Especially correlated with the ELM activity turbulence and TAE-mode activity reappears.

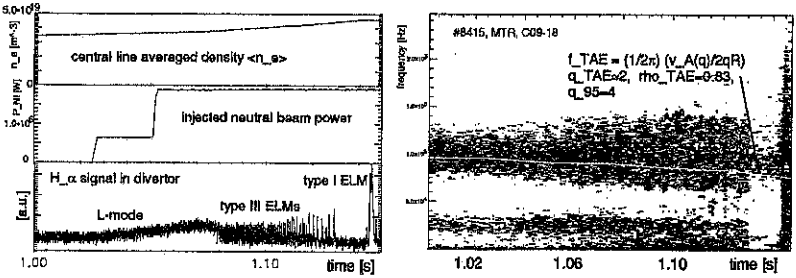

Figure 3: *Behaviour of the TAE-modes at the L- to H-transition. Correlated with the onset of the H-mode the TAE-modes disappear or are strongly reduced in amplitude.*

From TFTR similar mode activity observed on Mirnov coils has been reported [3]. The modes at TFTR were named Alfvén frequency mode (AFM) and were not consistent with the present TAE theory. In contrast to the results at TFTR the observed modes at ASDEX Upgrade could be identified as TAE-modes in the edge region of the plasma with the help of the resistive MHD-code CASTOR and the observation on the soft-X-ray diagnostic.

**excitation by drift Alfvén turbulence** A possible explanation for the excitation of these TAE-modes is the natural coupling to short wavelength drift Alfvén turbulence in the plasma edge. This mechanism would take place in two steps. In drift Alfvén turbulence, i.e. drift wave turbulence for which the magnetic induction associated with the fluctuating parallel current cannot be neglected, the parallel electric field is $E_{||} = -\partial A_{||}/\partial t - \nabla_{||}\phi$, with the induction term controlling the speed of the electron parallel dynamics [4,5,6]. This $E_{||}$ is coupled to the ExB turbulence by $\nabla_{||}p_e$ in the generalized Ohm's law. It is therefore unavoidable that electron drift turbulence and shear Alfvén waves are coupled at short perpendicular wavelength.

The second step is the transfer of this short wavelength Alfvén activity into global-scale modes via the well known 2D MHD inverse cascade in both ExB and magnetic energy. The finite range of both perpendicular and parallel wavelengths excited in the three dimensional turbulence makes it likely that some of this Alfvénic activity can find its way into the TAE-modes, since the curvilinear flux surface geometry prevents any particular mode number from being isolated. A broad interaction spectrum is consistent with both the CASTOR antenna spectrum (Fig. 1b) and the observations (Fig. 2a).

In addition, the TAE-modes are observed to propagate in the electron drift direction, which is consistent with the tendency of drift Alfvén turbulence as electron drift dynamics, and the tendency of edge fluctuations in general to be suppressed in the H-mode is consistent with the observation that the TAE activity becomes much less prominent in the H-mode.

All of this differs from the mechanism of the so called AFM activity in the absence of fast particles proposed by the TFTR group [3]. The activity seen in ASDEX Upgrade can be confidently identified as TAE activity which could be correlated with plasma edge turbulence.

**Summary and conclusions** The observation of TAE-modes in ohmically heated plasmas without fast particles has been reported. A consistent picture of the continuous TAE-modes in ohmically heated discharges with the help of the CASTOR code has been presented. A new idea has been proposed how TAE-modes could be excited without nonthermal fast particles by drift Alfvén turbulence in purely ohmically heated discharges.

## Acknowledgment

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