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# Alfvén Instabilities in WENDELSTEIN 7-AS

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## Abstract

Global Alfvén eigenmodes excited by resonant neutral beam injected fast ions cause a pronounced MHD activity in W7-AS. The characteristics of these modes in different parameter regimes are described. In particular, improved reconstructions of mode structures have been obtained by X-ray tomography. The effect of increased magnetic shear on the Alfvén spectrum and fast particle effects will be discussed.

## Keywords:

Alfvén Eigenmodes, neutral beam injection, fast particles, X-ray tomography, MHD-activity, magnetic shear

## 1. Introduction

The excitation of Alfvén Eigenmodes (AE) by energetic particles is an important issue because the associated magnetic perturbations may cause increased losses of resonant particles, in particular of fusion born alpha particles in a fusion reactor. Such losses can lead to a reduced margin for ignition and also to excessive heat loads on the vessel wall. First observations of alpha-particle-driven toroidal Alfvén eigenmodes (TAE) were made in the TFTR tokamak [1]. Most of the experimental investigations, however, refer to plasmas with energetic particle populations, which originate from the heating by neutral beam injection (NBI) or ion cyclotron resonance heating (ICRH). The experimental determination of AE frequencies and damping rates has been successfully achieved in the JET tokamak by using antenna excitation [2]. Considerable progress has been made to describe the present experiments by theoretical models thus providing a more reliable basis for predictions of the AE stability in future machines such as ITER. The magnetic configuration in W7-AS is characterized by non-axisymmetry, very low shear and large aspect ratio, and therefore, the Alfvén spectrum is expected to differ with respect to a typical tokamak case. The observations in W7-AS can potentially contribute to a broader understanding of Alfvén instabilities in toroidal systems.

During neutral beam injection in W7-AS pronounced MHD activity is observed, which is attributed to global Alfvén eigenmodes resonating with ions of the slowing down distribution [3]. In most cases net-current-free plasmas are investigated. Two almost tangential beamlines injecting in co- and counter-direction, each with a power of up to about 1.5 MW at 50–55 kV, into target plasmas generated by electron cyclotron resonance heating (ECRH) at magnetic fields of 1.25 T and 2.5 T or by a 900 MHz generator at arbitrary field, respectively. Usually hydrogen is injected into a deuterium target plasma (H → D), but D → D injection has

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been used occasionally in order to study fast particle effects by monitoring the beam-target neutron rates.

## 2. Low Frequency GAE Modes

The rotational transform at the plasma edge is typically slightly above the main resonances at $\iota=1/3$, $1/2$, where the confinement is good due to the reduced number of possible resonances [4]. Therefore, the shear Alfvén continuous spectra defined by the simple dispersion relation $\omega^2=(k_\parallel \cdot v_A)^2$, with $k_\parallel=(m\iota-n)/R$, $v_A$ Alfvén speed, $\iota=1/q$ rotational transform, poloidal and toroidal mode numbers m,n do not extend to the zero frequency limit since $k_\parallel$ remains finite. In the gaps below the Alfvén continua weakly damped global Alfvén eigenmodes (GAE) of both helicities, $n/m>0$ and $n/m<0$, can exist. In the first case the mode helicity is in the same direction as of the equilibrium field, and very low frequency GAEs in the range of 10...40 kHz are typically found. The mode numbers correspond to low order values of m and n with the ratio n/m closest to the value of the rotational transform at the location of the mode. Toroidal coupling between modes of same toroidal mode number n and adjacent poloidal mode numbers m and $m\pm1$ does not play a role due to low shear, and therefore, TAE gaps and TAE modes as in tokamaks are not present at least in case of low m and n. Low frequency GAEs are mostly relatively coherent and appear as continuous oscillations on signals of various diagnostics. The particle drive is inferred from transient mode behaviour at the time, when a neutral injector is switched off. The decay of the mode activity corresponds to the slowing down of fast particles below the resonance velocity, and is therefore much faster than the decay of the plasma pressure. The GAE frequencies are still much larger than those of pressure driven modes or tearing modes in case of ohmic current drive (OH). The GAE modes show the characteristics of waves propagating with a real frequency in the plasma rest system. The propagation is in the direction of the fast ion diamagnetic drift (opposite to the case of the other modes), and this is in agreement with the excitation mechanism, where free particle energy is tapped from the spatial fast ion gradient. The condition for this to overcome the fast particle velocity space damping is approximately given by $\omega^*_{i,fast}/\omega_{GAE}>1$ [5].

New data on the spatial structure of GAE modes have been obtained with a 10-camera miniature soft X-ray system (MiniSoX) [6]. This system with a total number of 320 channels is mounted inside the vacuum vessel and provides tomographic reconstructions of the soft X-ray emissivity with good radial and poloidal resolution. Different regularisation schemes including an advanced maximum entropy method [7] and additional analysis methods such as singular value decomposition (SVD) were applied to reconstruct equilibrium profiles and mode structures. The mode structures usually extend over a large fraction of the plasma radius. In case of single peak spectra, the mode structures are consistent with the lowest mode numbers to be expected. Frequently, however, two or more peaks appear in the Alfvén spectrum. Two effects have been found to cause multiple frequency peaks: - firstly, modes of different toroidal mode numbers but same pitch n/m eg. (m,n)=(3,1), (6,2), (9,3), - secondly, modes of same poloidal and toroidal mode numbers but different numbers of nodes in their radial eigenfunction. The second effect shows the global waveguide mode structure of the GAEs.

In many cases, particularly at high magnetic field, the velocity of the injected ions does not reach the Alfvén speed. However, excitation of GAEs can occur through $m\pm1$ sideband resonances because of toroidal coupling and particle drift effects. The sideband resonance, which is at $v_A/3$ in the TAE case, can be as low as $v_A/10$ for GAEs because $k_\parallel$ can be different by this factor for m and $m\pm1$.

In quasi-stationary discharges coherent GAE activity does not seem to cause significant losses. Typical saturation amplitudes of the magnetic perturbations are about $\tilde{B}/B\leq10^{-4}$, which seem to be in a subcritical range. Only in transient phases at the start of NBI, where the velocity distribution can be more unstable, plasma energy losses in combination with larger mode ampitudes have been found.

## 3. GAE Activity at Higher Frequencies

Pronounced but less coherent and sometimes bursting GAE mode activity in the higher frequency range 100–500 kHz has been occasionally observed. The frequency spectrum in this range is more complex and typically contains several peaks and also broader features. The frequencies are consistent with GAE modes of higher poloidal mode numbers with typically $m=5-8$ for $n=1$ or even higher in case of $n>1$. Additional gap modes such as toroidicity or ellipticity induced AEs (TAE, EAE) can also be present in case of higher mode numbers. Individual mode structures could not be experimentally identified so far, but the frequencies, which scale with the Alfvén speed, are in the range, where strong AE resonances are predicted by the MHD code CASTOR [8-10]. There is some

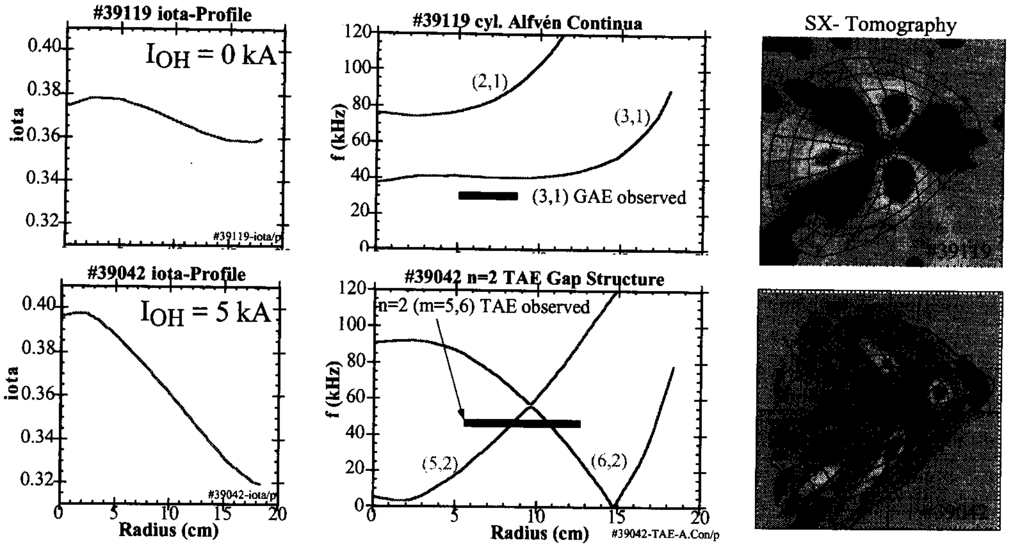


Fig. 1 Iota-profiles (left), Alfvén continuum gap structures (middle) and Alfvén mode structures obtained from X-ray tomography (right). In the case of low shear (zero toroidal current) the dominant mode is a (m,n) = (3,1) GAE in the gap below the continuum (top). Increased shear due to OH current drive causes a TAE gap for n=2, and the mode structure is dominated by m=5 (inner part) and m=6 (outer part) consistent with the n=2 TAE mode (bottom).

evidence for enhanced transport due to this activity, probably because of multiple resonances. The appearance of the high frequency modes is correlated with the condition, that the Alfvén speed is below the full energy fast particle velocity. Only under this condition GAEs with higher mode numbers can resonate with the fast ions, since in this case the sideband resonance velocities do not differ very much from $v_A$. The transition from sideband to fundamental resonance dominated excitation is clearly seen during density ramps, when $v_A$ drops below $v_{beam}$. Simultaneously with the onset of the high frequency AEs the activity at low frequencies becomes weaker indicating that the available free energy is redistributed.

## 3. Transition from GAE to TAE Modes

In order to investigate the effect of shear on the GAE stability and to show the common physics of GAEs and TAEs shear variation experiments were performed by driving toroidal currents in both directions with the OH transformer. With respect to stability no conclusive result has emerged, since confinement, and therefore, plasma parameters depend on the iota profile. However, evidence for TAE modes at higher shear was found by soft X-ray tomography (Fig. 1) in spite of the narrow TAE gap due to large aspect ratio. The observed frequency is consistent with the Alfvén gap structure for $n=2$, and the spatial structure is

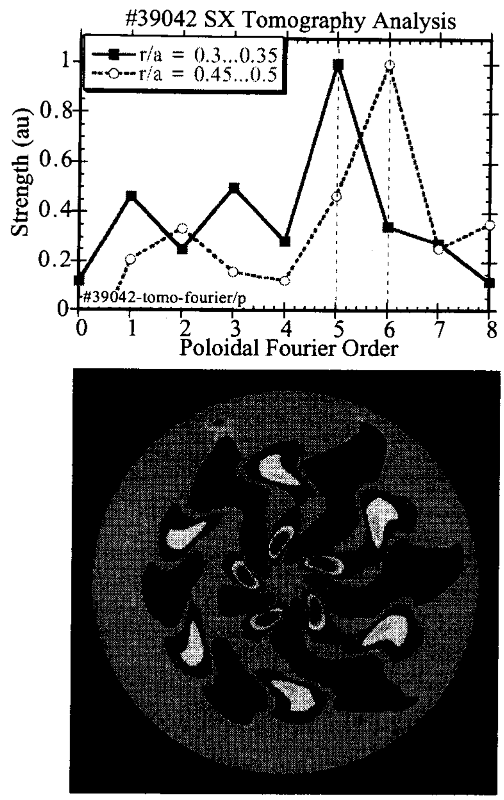


Fig. 2 Poloidal Fourier analysis of SX tomogram (top) for #39042 (Fig. 1) yields $m$=5 in the inner part and m=6 further out in qualitative agreement with gyrofluid model calculations (bottom).

dominated by m = 5 and m = 6 as expected for the n = 2 TAE. A MHD code with a gyrofluid model for the fast particles [11], which explains the main features of the GAE modes, also gives consistent results for the TAE case (Fig. 2).

## 4. Conclusions

The basic observations of beam driven modes are consistent with global Alfvén eigenmodes. New information about the internal mode structure was obtained from X-ray tomography analysis. As soon as the Alfvén velocity becomes low enough, modes in the higher frequency range are destabilized. With increasing shear a transition of the GAE to TAE type occurs. The effect of Alfvèn instabilities on the fast particle confinement is not yet clear. Global Alfvén eigenmodes cannot be suppressed by avoiding rational surfaces, since their eigenfunctions do not peak there. Therefore they are of potential danger in plasmas with a large fraction of ions in the super-alfvénic range.

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