

# STUDY OF ALFVÉN EIGENMODES IN CONFIGURATIONS OF DIFFERENT SHEAR AT WENDELSTEIN 7-AS

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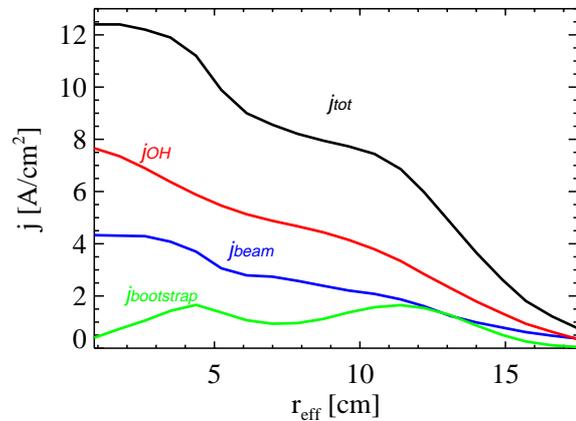
## 1. Introduction

Alfvén eigenmodes are widely investigated in fusion experiments, since they are expected to be destabilized by energetic particles and eventually may cause losses of fast alpha particles in future fusion reactors. In current experiments, NBI-driven Alfvén eigenmodes are seen in stellarators and tokamaks but they differ by the way of mode formation. In the stellarator case with low shear the Global Alfvén Eigenmode (GAE) below the Alfvén continuum is expected, whereas in a tokamak-like case with high shear, Toroidal Alfvén Eigenmodes (TAE) are the dominant mode types.

Beside low shear, the advanced stellarator W7-AS is characterised by large aspect ratio (about 12) and a 3D-field geometry, which also influences the Alfvén spectra. The study of GAE modes in W7-AS can possibly be related to reversed shear scenarios in advanced tokamak experiments, where extended regions of low shear are present. On the other hand, by increasing the shear in W7-AS, the common physics of Alfvén eigenmodes in stellarators and tokamaks can be investigated in studying the transition from GAE to TAE modes depending on the profile of the rotational transform.

We compare experimental results with expectations based on the Alfvén continuum spectra, with numerical calculations using a gyrofluid model [1] and with a 3-dimensional MHD-code CAS3D [2].

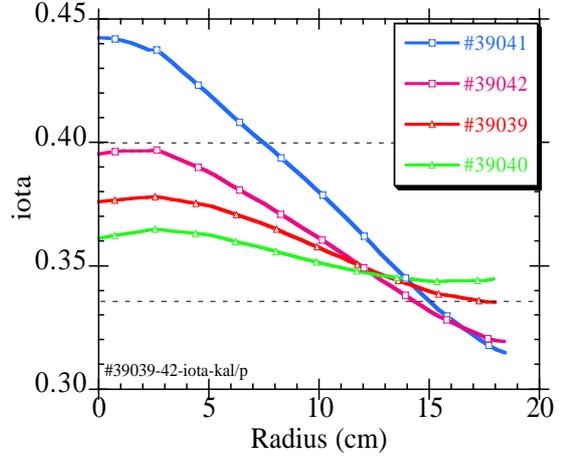
In W7-AS, shear is modified with respect to the vacuum configuration by equilibrium currents (Pfirsch-Schlüter), bootstrap- and beam-driven Ohkawa-currents, which are usually compensated by an inductively driven current in order to achieve net-current-free operation. In the experiments described here, shear is changed by driving a plasma current of up to 12kA in both directions as shown for example in Fig. 1. Positive and negative shear can be generated, allowing to investigate a variety of different Alfvén continua including cases with GAE and TAE gaps.



**Figure 1: Current densities in W7AS for shot #39042.** Here, all currents are positive and a net total current is driven in order to increase the magnetic shear.

## 2. Experimental Plasma Set-up

Experiments are done with the standard magnetic field of  $B = 2.5T$  and different values of the ohmic current to change strongly the shear of the magnetic configuration. In order to keep the edge value of the rotational transform  $\iota_a$  constant, the vacuum iota  $\iota_a^0$  was adjusted depending on the ohmic current. See Fig. 2 for a sequence of  $\iota$ -profiles with different magnetic shear but almost equal  $\iota_a$ . Plasma heating is done purely with neutral beam injection (NBI), the ohmic power is negligible. Balanced injection is used in most cases to avoid effects from toroidal plasma rotation on mode frequencies and to minimize the beam-driven plasma currents. Usually a density ramp is performed to enable the study of mode frequencies that should scale like the Alfvén velocity  $v_A = B/\sqrt{\mu_0\rho}$  ( $\rho$ , mass density). The energy source for the excitation of Alfvén eigenmodes is provided by resonant fast particles from the NBI.



**Figure 2: Magnetic shear-variation from ohmic current drive in W7AS.** All profiles are sheared negative (positive shear in  $q$  in tokamaks).

## 3. MHD Diagnostics

An important tool to analyse the mode structures is a tomographic system for the soft-X radiation, composed of 10 cameras inside the vacuum vessel with a total number of 320 viewing chords [3]. The 2-D mode reconstructions can be done without assumptions about the magnetic topology. The spatial resolution is around 1cm and tomographic reconstructions with experimental data showed the potential to identify structures up to poloidal mode numbers of  $m = 9$  and a radial mode number  $s = 1$ . The sampling rate is up to 200kHz, which is sufficient for analysing Alfvén-eigenmodes with typical frequencies of 30kHz at W7-AS. Singular value decomposition (SVD) and filtering in the frequency domain on a rectangular grid radially limited by the borders of the soft-X profile, proved to be good tools for extracting the fluctuating part of the soft-X emission [3].

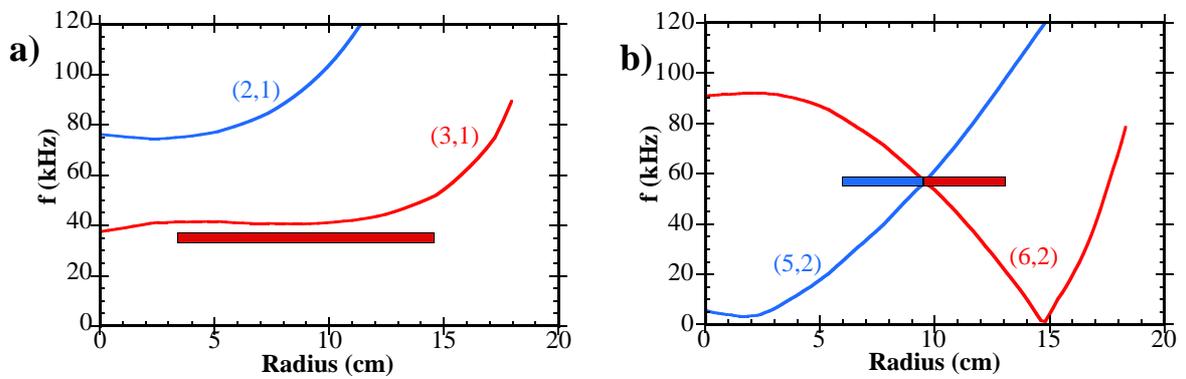
Since the soft-X emission is restricted to the hot plasma region (up to 70% of the plasma radius  $a$  for NBI discharges), the ECE diagnostic (100kHz sampling), reflectometry (1MHz) and magnetic pick-up coils (250kHz) are used to check the tomographic reconstructions and to get further information about the mode structure near the plasma edge. The comparison of different diagnostics can be made in terms of the radial displacement of flux surfaces as deduced from the measurements.

## 4. Transition from GAE to TAE modes with increasing magnetic shear

Alfvén eigenmodes like the GAE and TAE mode, which extend over a large part of the plasma cross-section are predicted to occur as weakly damped discrete solutions in the mag-

neto hydrodynamic (MHD) spectrum. They typically occur in frequency gaps of the continuous branch of solutions, the so called *Alfvén continuum*, consisting of a strongly damped class of radially localized eigenmodes. The frequencies of the Alfvén continua are given by the local dispersion relation  $\omega^2 = (k_{\parallel} \cdot v_A)^2$ , with  $k_{\parallel} = (m \mp n)/R$  the parallel wave number,  $n$  the toroidal mode number and  $R$  the major radius. The dependence on the  $\mp$ -profile causes a characteristic difference in the gap structure of tokamaks and low shear stellarators. Two possible ways of gap formation are shown in Fig. 3. In the tokamak case with a strong shear a TAE mode contains a large number of poloidal harmonics, where the dominant poloidal mode number is inherited from the nearest Alfvén continuum at the same radius (see e.g. [4]).

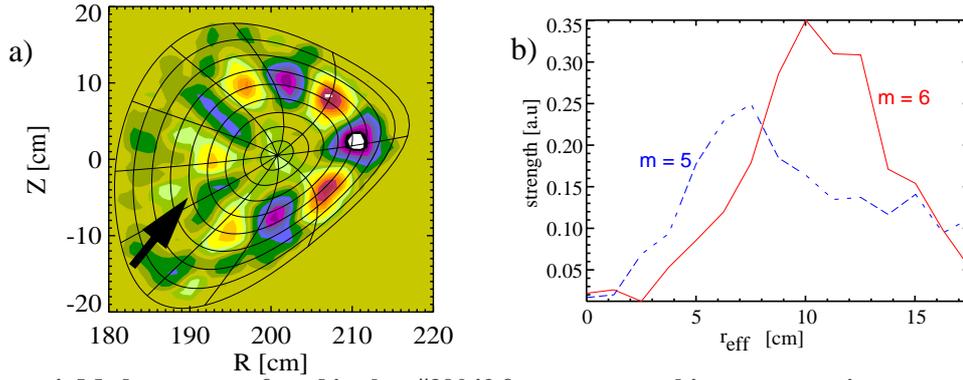
In contrast, the low shear at W7-AS usually leads to a well defined  $(m, n)$ -structure of a GAE [5] (like in Fig. 3a). In discharges at  $\iota_a \approx 0.35$ , we increased the shear using ohmic currents such to create a TAE gap for  $n = 2$ , where only two adjacent poloidal mode numbers ( $m = 5$  and  $6$ ) are involved over the whole plasma cross-section (discharge #39042 in Fig 2 and Fig. 3b). Experimentally, we indeed found the predicted TAE mode at a frequency of 63 kHz. This is a case, for which the full 2-D mode structure of a TAE mode could be obtained for the first time by soft-X tomography (Fig. 4a). Both components, the  $m = 5$  in the inner region and the  $m = 6$  in the outer region are seen in the tomograms in accordance with the expectations. The contributions of these two components to the mode eigenfunction have been derived quantitatively by poloidal Fourier analysis of the tomograms (see Fig. 4b). A comparison to theoretical expectation was done in 2 ways. First, numerical calculations of the linear growth rates with a gyrofluid code [1] taking into account the fast particle physics but using an axisymmetric approximation shows the destabilization of the mode. Secondly, to compare the mode structure calculations in the stable part of the MHD spectrum were performed using the CAS3D stability code which uses the proper 3-D equilibrium information, but neglects fast particles. Also there, TAE modes were found as discrete solutions with radially extended eigenfunctions. A comparison of the radial distribution of the leading Fourier harmonics (Fig.4 and 5) shows a slight disagreement in the radial position which may be due to uncertainties in the profiles entering the equilibrium and the CAS3D calculations. Good agreement



**Figure 3: Alfvén continua for low (a) and increased magnetic shear (b).**

a) GAE mode (plotted bar) in the gap below the (3,1)-continuum.

b) TAE gap mode in the gap induced by coupling of to two continua with  $(\Delta m, \Delta n) = (1, 0)$ .

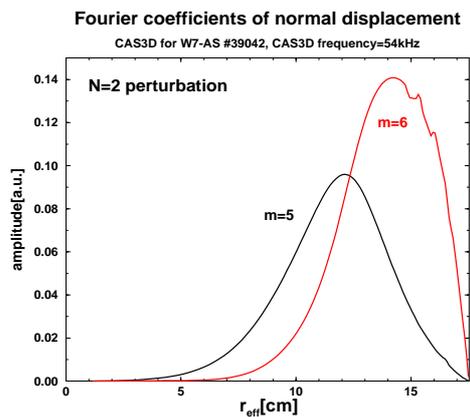


**Figure 4: Mode structure found in shot #39042 from tomographic reconstruction.**

- a) Poloidal cross-section of the mode structure. The arrow marks the radial position, where the  $m = 5$  structure changes to  $m = 6$  (at  $r_{\text{eff}} = 9.5$  cm)
- b) Radial distribution of Fourier-harmonics with  $m = 5$  and  $6$  from tomographic reconstruction. The mode frequency in the laboratory frame is 47 kHz.

was found for the frequencies, if the Doppler shift in the measured frequency due to poloidal plasma rotation (-15 kHz) is accounted for.

Taking the shear value in the TAE-case as a reference, with increasing shear first the formation of a rational surface  $\iota = 2/5 = 0.4$  is observed by the appearance of a pressure driven mode, which exists in the presence of the TAE mode. Further increase of shear leads to only weak mode-activity, that cannot be analysed anymore. With decreased shear (#39039 and #39040 in Fig. 2), GAE modes with  $m = 3$  or  $m = 5$  were found in accordance with the expectations together with additional mode activities. An attempt was made to excite TAE modes with different mode numbers by changing the edge rotational transform. First results indicate the presence of the TAE modes with the expected poloidal mode structure. These observations demonstrate the close relationships between the structure of global Alfvén eigenmodes in stellarators and tokamaks. More studies are needed to explain in particular the conditions for the destabilization of the different modes and their effect on the fast particle confinement.



**Figure 5: Mode structure found in shot #39042.**

CAS3D-eigenvector for a  $n=2$  perturbation with a frequency of 54 kHz [6].

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