

CONF-9505254--6

Global Alfvén Eigenmodes in WENDELSTEIN 7-AS

(10th International Stellarator Conference, 22-26 May 1995, Madrid, Spain)

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1. Introduction.

In the presence of fast particle populations marginally stable global modes in the shear Alfvén branch can be destabilized by wave particle resonances. This is particularly of concern in future large devices, where losses of resonant particles (α -particles in a reactor) may then limit the available heating power and also may cause damage of the first wall. In tokamaks TAE modes inside toroidicity induced gaps of the shear Alfvén continua have been found [1,2]. In stellarators with very weak shear like W7-AS low-n TAE-gaps do not occur but gaps below the shear Alfvén continua with mode numbers m and n , if the resonant values $\dagger = n/m$ do not exist in the plasma volume ($k_{\parallel} = (m \cdot \dagger - n)/R \neq 0$). Under these conditions GAE modes with frequencies $\omega_{\text{GAE}} \leq (k_{\parallel} \cdot v_A)_{\text{min}}$ are the favoured modes [3]. The investigation of GAE modes could also be of relevance in the case of advanced tokamak equilibria with flat or inverted q -profiles in the central region [4].

2. Experimental Results.

GAE modes with frequencies in the range 10-70 kHz (Fig. 1) have been studied in W7-AS during neutral beam injection (NBI). The fast particle drive is inferred from the transient

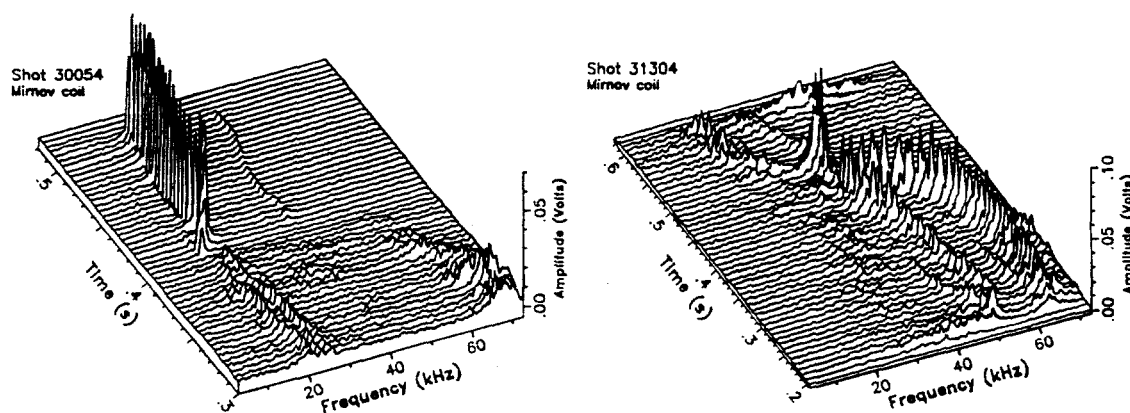


Fig. 1: Frequency spectra (Mirnov coil) showing GAE activity. Left: (3,1) modes grow at transition to low energy ($t = 0.4$ s, "density limit" reached, $B = 1.25$ T). Right: high temperature case at $B = 2.5$ T. The frequency decreases with increasing density.

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mode behaviour during NBI switch-on/off, since the mode decay is much faster than the fast ion slowing down time and the time in which the plasma pressure changes. The understanding of the conditions, under which the GAE's are driven unstable, is still an issue under investigation. These modes are preferentially excited in phases, where the plasma energy has already started to decay as the density limit is approached, which is determined by the available heating power. In this case the energetic particle drive ($\propto \beta_{\text{fast}}$) is expected to decay faster than the electron Landau damping ($\propto \beta_e$). The experiments together with gyrofluid code calculations indicate, that additional effects connected with changes of the magnetic shear, of the Alfvén velocity, of the beam deposition and fast particle profiles, and of the beam slowing down distribution have to be taken into account. Particularly in the higher β range ($\langle \beta \rangle > 0.5\%$) the modes disappear probably due to increased continuum damping, since the internal shear is increased by the pressure induced equilibrium currents. Recently a new parameter regime of GAE activity was found at high temperature and relatively low density (combined NBI and ECRH, $T_e, T_i > 1$ keV, $n_e < 6 \cdot 10^{13} \text{ cm}^{-3}$) with frequencies up to 70 kHz. Under these conditions the fast ion drive is larger, whereas the iota-profile can still be flat due to low plasma β and effects associated with the bootstrap current.

The modes are identified in terms of Alfvén waves by their frequency in the plasma rest frame and the dependency of their frequency on the Alfvén velocity. This was investigated (Fig. 2) by varying the magnetic field (in the range 0.7-2.5 T) and the mass density

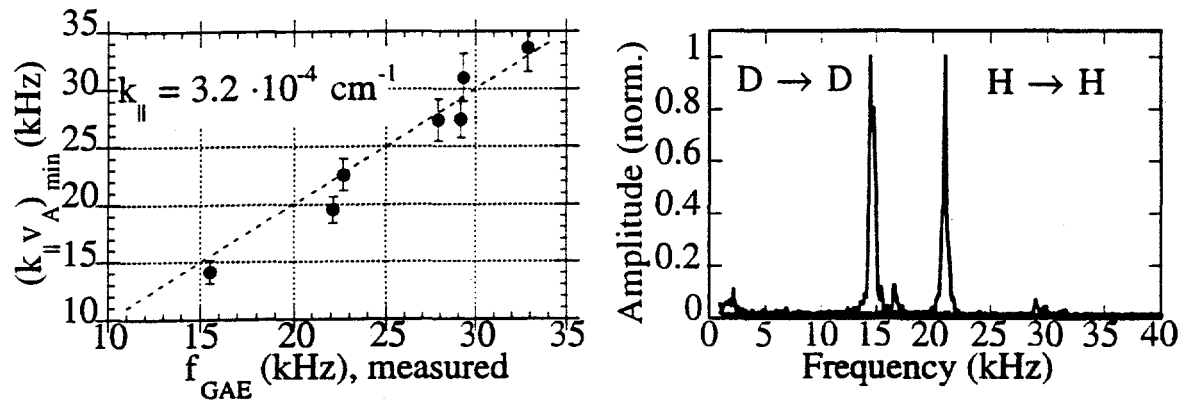


Fig. 2: Variation of the Alfvén velocity by a magnetic field scan (left) and by mass density (right, comparison of similar shots with H- and D-injection). The observed frequencies depend on the Alfvén velocity.

(comparison of similar discharges of H → H with D → D injection). The propagation of the modes is in the direction of the (fast) ion diamagnetic drift as expected, since the drive energy originates from the fast particle drift motion in conjunction with their spatial gradient. Apart from transient phases during NBI switch-on the fast ion distribution in velocity space leads to Landau damping (in addition to electron Landau damping and other damping mechanisms).

The spatial mode structure is determined from reconstructions using data from soft X-rays, ECE, reflectometer and Mirnov coils. The radial structure corresponds to global modes,

which extend over up to half of the plasma radius. The helical structure agrees with the lowest possible mode numbers m and n , which are aligned most closely with the equilibrium field. Since the corresponding resonant surface with $\frac{r}{R} = n/m$ is not contained in the plasma, the magnetic perturbations are of non-resonant type (small but finite k_{\parallel}). In most cases the Alfvén velocity is found to be larger than the energetic particle velocities. Therefore, the modes are excited via toroidal $m \pm 1$ sideband resonances with $v \ll v_A$.

3. Comparison with Theoretical Predictions.

Global modes have been found in MHD calculations including a gyrofluid model for the fast particles [5,6]. The model takes various damping effects (eg. continuum damping, Landau damping, effects of collisional damping and resistivity) into account. The frequencies are consistent with the GAE gap structure of the low (m,n) shear Alfvén continua and agree with the experimental data. Also the spatial structures and saturation amplitudes correspond to the experimental data. The calculations show, that the stabilization at higher β (in the high density, low temperature regime) is the consequence of enhanced continuum damping due to increased shear in combination with reduced fast ion drive. The model also verifies, that the energetic particle destabilization of GAE's in W7-AS mainly occurs by ions with parallel velocities clearly below v_A . In most cases, where GAE's are found, the full energy ions (45 keV) do not reach v_A in the plasma core. The destabilization, therefore, takes place via the toroidal $m \pm 1$ sideband drift resonances at much lower particle velocities $v_{\text{res}} = |\omega_{\text{GAE}} / k_{\parallel, m \pm 1}| \ll v_A$, since $|k_{\parallel, m \pm 1}| \gg |k_{\parallel, m}|$ due to the observed mode helicity (same as for equilibrium field) and weak shear in W7-AS. The contributing particles in the slowing down distribution are mainly those injected with 1/3 of the full NBI energy

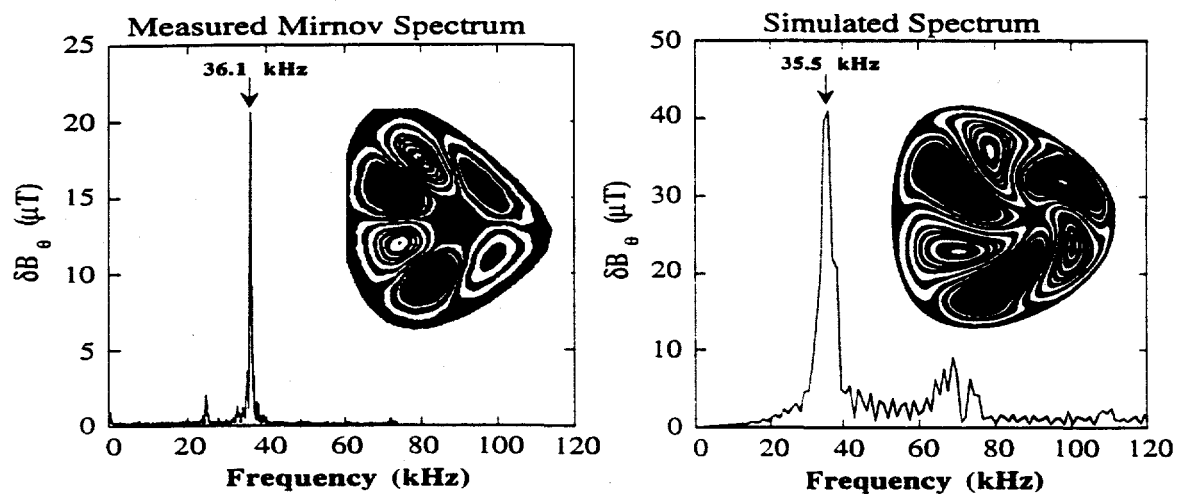


Fig. 3: Measured and calculated (nonlinear calculation) GAE frequency spectra and mode structures ($m=3, n=1$).

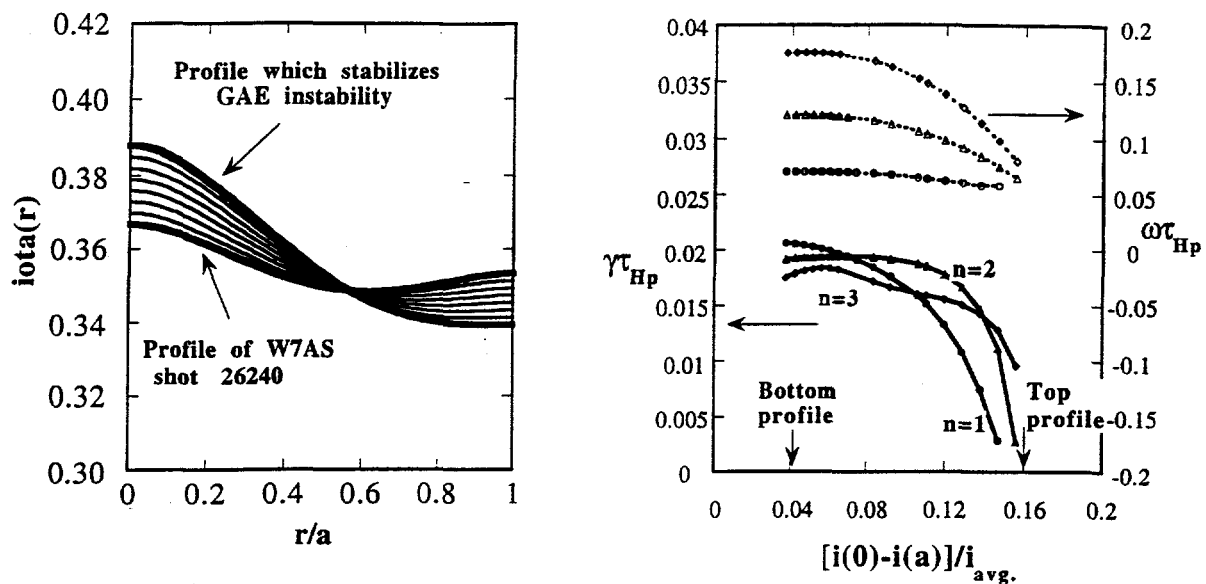


Fig. 4: The stability of GAE modes depends on shear (gyrofluid calculations). Left: q profiles used in the calculation. Right: linear growth rates vs. shear parameter.

4. Conclusions.

The main features of the observed beam driven MHD instabilities in W7-AS can be explained in terms of global Alfvén modes. Although for particular cases quantitative agreement was found with theoretical predictions, it seems difficult to make quantitative predictions of the stability of these modes in general, because effects both of the damping by the main plasma and the drive due to the fast particles cannot be separated clearly. Therefore, investigations have been started to study the Alfvén spectrum and the damping mechanism by launching waves with an external antenna [7]. No evidence of GAE induced particle or energy losses has been found so far, the observed magnetic perturbations of $\bar{B}_\theta/B \leq 10^{-4}$ at the plasma edge agree with nonlinear gyrofluid calculations and seem to stay below critical values. Experiments with deuterium injection have been started in order to improve the diagnostics of energetic particle losses by exploiting the neutron flux. The experiments in W7-AS in conjunction with code calculations are considered to provide useful information concerning the issue of α - and beam-driven instabilities in future machines., in particular those with extended regions of weak shear.

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