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Correlation between MHD-activity, energetic particle behaviour and anomalous transport phenomena in WENDELSTEIN 7-AS

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Introduction - Energy and particle transport in W7-AS exhibits a resonance-like dependence on the edge rotational transform (iota) as long as the magnetic shear is relatively weak (low β, no significant net toroidal currents). MHD modes at resonant surfaces may cause enhanced radial transport depending on the magnitude and radial extent of the magnetic perturbations. In many cases discharges in W7-AS are very quiescent, or in case of mode activity, often no influence on energy and particle confinement is found. In the high beta regime ($\langle\beta\rangle \leq 1.8\,\%$) shear is increased due to the effect of the Shafranov shift leading to the formation of rational surfaces inside the plasma. Pressure driven mode activity appears at corresponding resonant surfaces. These modes could be resistive interchange instabilities since the respective stability criterion can be violated at least in the outer part of the plasma. Only around the highest beta values and in cases, where the magnetic well of the configuration was reduced, relaxations of the plasma energy are observed, indicating the vicinity of a soft beta-limit. In most cases, however, the maximum achievable beta is determined by the available heating power.

Effect of NBI driven global Alfvén Eigenmodes on plasma confinement - Most of the MHD activity observed occurs during neutral beam injection (NBI) in the lower beta regime, where low order rational surfaces can be avoided due to the very low shear of the configuration. Therefore, away from but close to resonant surfaces gaps in the shear Alfvén spectrum are present, where global Alfvén eigenmodes (GAE) can be excited by resonant fast ions of the beam distribution. In NBI heated plasmas GAE activity often coincides with the iota-range of degraded confinement. However, this is also the range where formation of low (m,n) Alfvén gaps becomes possible. Since the resonant confinement degradation also occurs during ECRH, where no fast ion population is present and only very weak MHD-activity is observed, it is conjectured, that magnetic turbulence phenomena around the dense high (m,n) resonant surfaces are causing this effect. From the analysis of iota-profiles it is concluded, that the main low (m,n) resonances are less unfavourable because their neighbourhood is free of resonances. In the period after switch on of NBI very pronounced GAE activity causing enhanced transport can be excited due to transiently unstable fast ion velocity distributions. In particular, when the target plasma has very low density or the discharge is initiated by the neutral beams, even more unfavourable fast ion distributions can be formed due to charge exchange effects. In this case in addition to the low frequency (20 - 40 kHz), low (m,n) GAE-activity a broad frequency range of activity extending up to 500 kHz is found by magnetics and various fluctuation diagnostics. The origin of this activity can be explained by Alfvén modes of higher mode numbers. GAE's, but also global Alfvén modes in gaps induced by ellipticity or higher non-symmetry (EAE, NAE) could play a role. Fig. 1 shows the change of the frequency spectrum (Mirnov coil) with the change of the Alfvén speed. Simulations of a (virtual) antenna loading spectra with the

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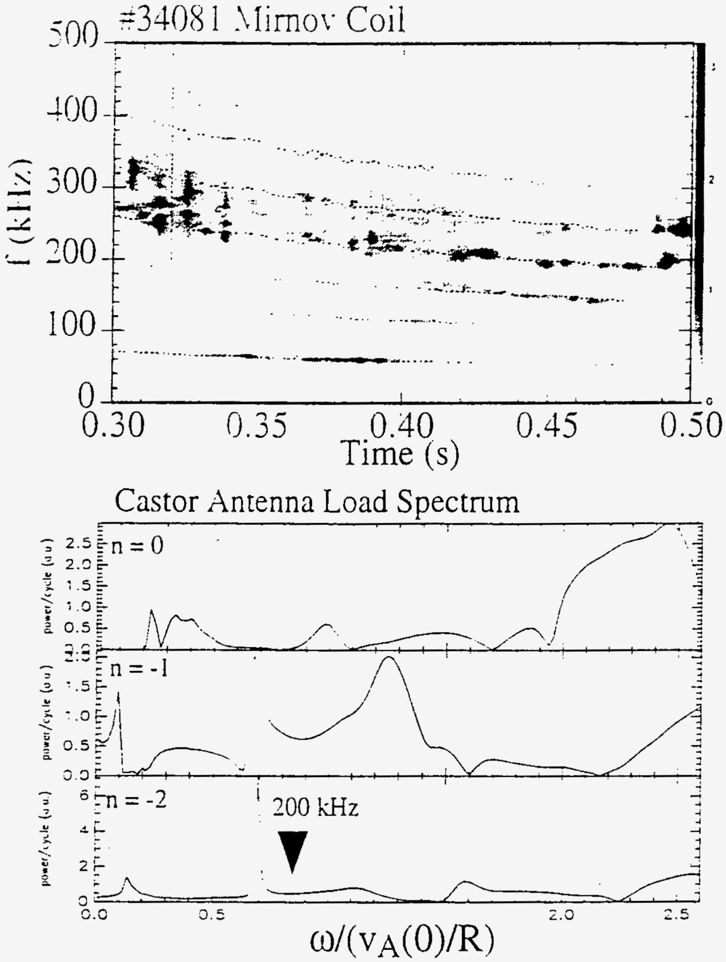

Fig. 1: Global Alfvén frequency contours (top) during NBI density ramp. The dashed lines indicate the temporal evolution of the Alfvén speed. Bottom: antenna loading spectrum calculated with the CASTOR code for n=1,2,3.

neutral beams, even more unfavourable fast ion distributions can be formed due to charge exchange effects. In this case in addition to the low frequency (20 - 40 kHz), low (m,n) GAE-activity a broad frequency range of activity extending up to 500 kHz is found by magnetics and various fluctuation diagnostics. The origin of this activity can be explained by Alfvén modes of higher mode numbers. GAEs, but also global Alfvén modes in gaps induced by ellipticity or higher non-symmetry (EAE, NAE) could play a role. Fig. 1 shows the change of the frequency spectrum (Mirnov coil) with the change of the Alfvén speed. Simulations of a (virtual) antenna loading spectra with the CASTOR code [1] reveal a number of resonances in the frequency range of the experimental data. The high frequency activity has set in later than the low (m,n) GAE's, which can already be excited by sub-Alfvénic beam ions via toroidal sideband excitation. For a number of cases also MHD calculations of Alfvén instabilities were performed with a gyrofluid model for the fast particles [2], which are consistent with the observed MHD activity. The analysis of mode structures, which is important for comparisons with theory, has been improved by a 10-camera soft X-ray system with 320 channels [3] and new analysis techniques for the magnetic probes [4].

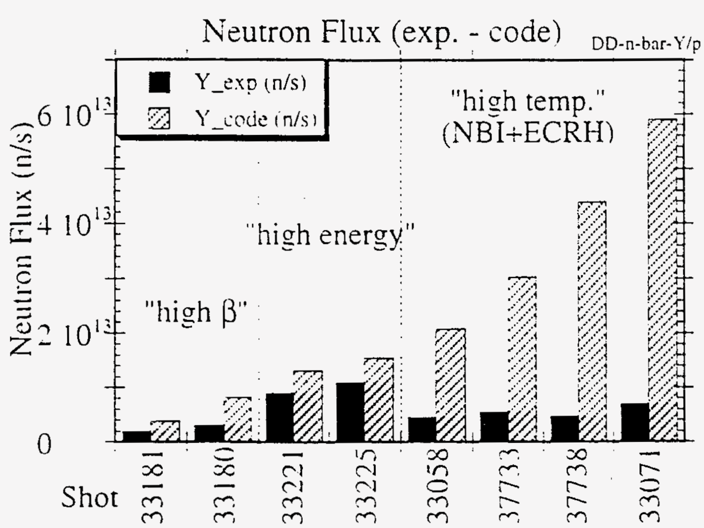

Fig. 2: The discrepancy between measured and calculated neutron rates increases at low collisionalities with increasing slowing down times (selected shots)

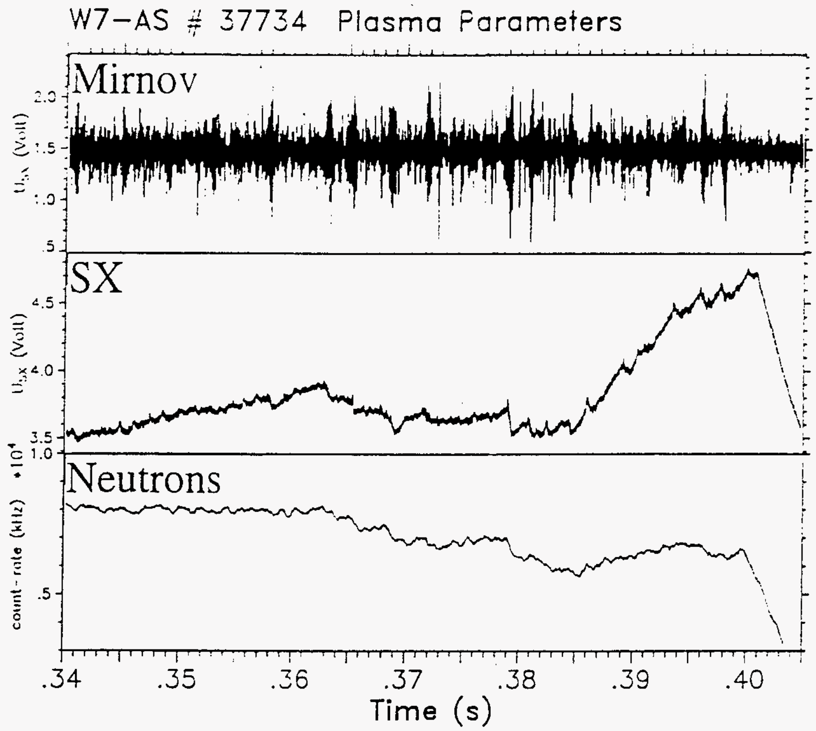

Fig. 3: Correlation between GAE bursts and reaxations of the soft X-ray intensity and neutron rate

Another regime where strong effects on transport are caused by beam driven Alfvén modes is at low electron collisionality achieved with combined ECRH and NBI heating. Under these conditions the classical slowing down time can be up to 50 ms exceeding clearly the energy confinement time. A transition from continuous GAE modes to bursting GAE activity occurs, which is accompanied by losses of fast particles and thermal plasma energy. This has been inferred from data obtained with deuterium injection using the neutron rate as a measure of the fast particle density since beam-target reactions are the dominating neutron production process. The magnitude of the stationary neutron flux was found to be significantly lower than predicted values (fig. 2), and in addition, relaxations of the D-D neutron rate and soft X-ray signals in correlation with the MHD bursts are observed (fig. 3). The loss rate of energetic particles, can be estimated roughly from $\tau_{fast} \approx \Delta t \cdot (\Delta\phi/\phi)^{-1}$, where Δt and $\Delta\phi/\phi$ are the average time between bursts and the average relative drop of the neutron flux, respectively. The fast particle confinement times derived in single cases are of the order of the slowing down time. Since resonances often occur with ions of relatively low velocities (< 1/3 injection velocity), which do not contribute to the neutron production, this analysis may underestimate the total loss rate.

Alfvén modes in the absence of fast particles - MHD activity presumably due to GAE modes is also observed in ECRH plasmas without NBI. These modes are weaker as compared with NBI driven GAE modes and are preferentially seen under degraded confinement conditions without being the direct cause of enhanced thermal transport. Whereas during NBI the propagation is in the (fast) ion diamagnetic drift direction as expected from the ion drift excitation process, it is opposite during ECRH only. The frequencies are consistent with GAE modes inside the lowest Alfvén continuum gap (fig.4). The observations are similar to results of TFTR [5] and ASDEX Upgrade [6] where TAE modes were found in the OH phase. A possible excitation mechanism considered recently is the coupling of $\mathbf{E} \times \mathbf{B}$ turbulence to

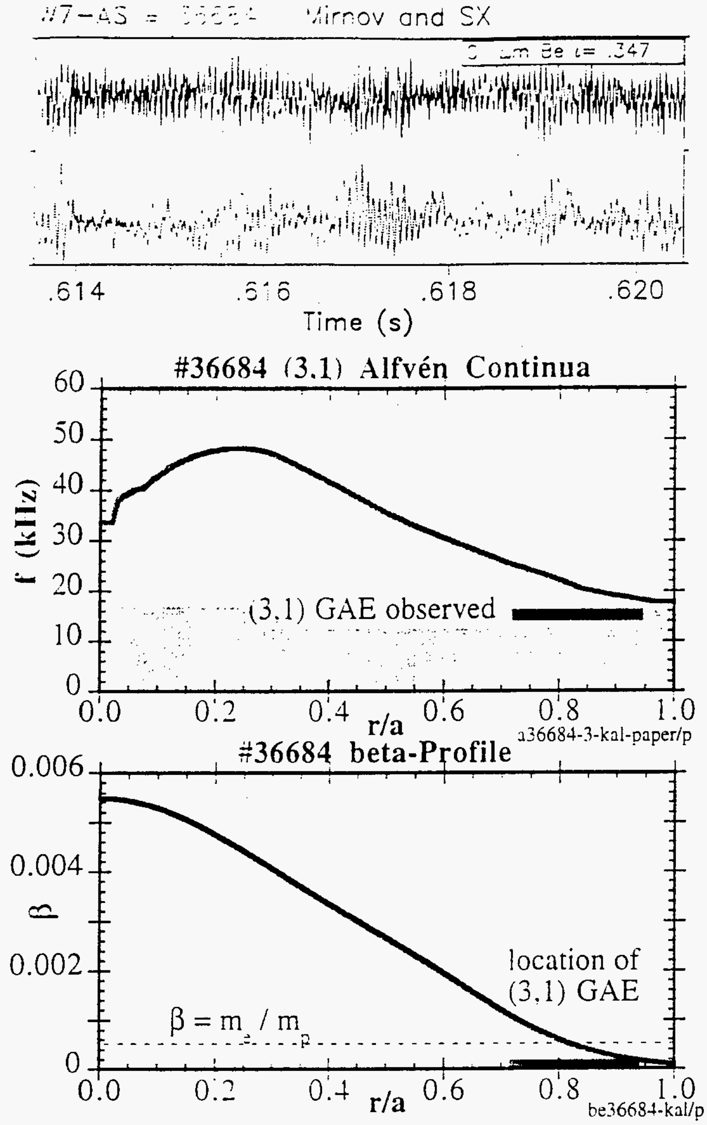

Fig. 4: Global Alfvén Eigenmodes (GAE) in ECRH plasma (Mirnov and SX signals top), Alfvén gap structure (middle) and beta profile (bottom).

electromagnetic drift Alfvén turbulence cascading into low $k_{||}$ Alfvén waves [7,6]. The local β-values at the location of the modes is in the range where such coupling is expected (fig. 4, bottom). A correlation between MHD-activity, broadband turbulence and enhanced transport is found in many cases including NBI discharges.

Conclusions - The dependence of the confinement on the magnetic configuration cannot be explained simply by low (m,n) magnetic field resonances ("natural" islands and other static field perturbations) or mode activity. Global Alfvén modes emerge from the multiformity of MHD activity in W7-AS as most prominent instabilities. Since their propagation requires finite $k_{||}$ (or a gap in the continuous Alfvén spectrum), GAE modes with mode numbers (m,n) cannot be easily suppressed by avoiding the corresponding rational surface iota=n/m in the confinement region. The effect of Alfvén modes on energy and particle transport is significant only during transient phases of bursting modes and in the low collisionality regime with NBI. Drift Alfvén turbulence is considered to be an important process to explain both, the resonant anomalous transport and the excitation of GAE's in ECRH plasmas.

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