Excitation of Global Alvfén Eigenmodes by RF Heating in JET

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INTRODUCTION

The alpha-particle confinement of future D-T experiments at JET can be severly degraded by Global Alfvén Eigenmodes (AE). Scenarios for the excitation of Alfvén eigenmodes in usual (e.g. D-D) plasmas are proposed, which provide a MHD diagnostic and allow the study of the transport of super-Alfvénic ions.

Active studies with separate control of TAE amplitude and energetic particle destabilisation, measuring the plasma response, give more information than passive studies, in particular concerning the damping mechanisms. The linear regime of the Alfvén physics can be exploited for a MHD diagnostic, where no significant perturbation of the plasma is required.

The TAE excitation can be achieved by means of the saddle coils, modelled in Ref. [1,2], and the ICRH antenna. In this paper the experimental method is introduced together with a theoretical model for RF excitation.'

EXPERIMENTAL METHOD

Whereas the saddle coils constitute a direct drive of global Alfvén waves via oscillatory currents with a frequency range of 20 - 500kHz (covering BAE, TAE and EAE), the ICRH antenna operates at much higher frequencies. Direct excitation has, consequently, to be achieved by frequency/amplitude modulation or by the nonlinear interaction of two fast waves whose frequency differ by the AE frequency. The beat wave excitation, satisfying energy $(\omega_1 - \omega_2 = \omega_{TAE})$ and momentum $(\vec{k}_1 - \vec{k}_2 = \vec{k}_{TAE})$ balance, relies on the generation of a volume current, $\vec{j}_{n\ell}$, inside the plasma with a power transfer $\langle \vec{j}_{n\ell} \cdot \vec{E}^*_{TAE} \rangle$ into the TAE. The corresponding radial magnetic field amplitude can be large at marginal stability $(\gamma_{TAE} \rightarrow 0)$, $\delta B_r / B_0 \approx \omega_{TAE} / \gamma_{TAE} \cdot v^2_{osc} / v^2_A$. A second method is given by the generation of high-energy ions, which subsequently provide the drive for AE destabilisation. Due to the high power of the JET ICRH antennae, these methods could generate finite-amplitude AE, allowing a systematic study of the AE enhanced energetic particle transport.

In the active studies the frequency in the driver is swept, correspondingly the modulation amplitude/frequency or the difference between the two driving RF wave frequencies. When a global Alfvén eigenmode is encountered, a resonance appears in the plasma response. The corresponding width gives a measure for the damping.

Synchronous detectors, whose reference signal is taken directly from the saddle coil exciter or, in the beat wave case, from the frequency difference of the two fast waves, are used to diagnose the plasma response. In phase ('real') and quadrature ('imaginary') components are provided. Different signals (up to 48) are considered, namely the active saddle coils for the antenna impedance, the passive saddle coils for the perturbed $\vec{B}_r$ (n-mode analysis), the magnetic probes for the perturbed $\vec{B}_\theta$ (n- and m-mode analysis) and other space-resolved, non-magnetic diagnostics, such as ECE and reflectometry, to resolve the spatial mode structure

The Data analysis fits the antenna-plasma-detectors transfer function with a rational fraction, with the discrete AE resonances being represented as poles in the complex plane, where the real part corresponds to the frequency and the imaginary part to the damping or drive. When Alfvénic fast particles ($v \sim v_{\text{Alfvén}}$) are produced in the plasma, e.g. by ICRH or NBI, an AE instability driving effect is produced and the imaginary part of these poles is modified.

WAVE-PARTICLE INTERACTION

Theoretical estimates for the RF drive of the TAE mode are based on a perturbative approach valid for a small drive. In the hybrid kinetic-MHD model a quadratic form is constructed, where the non-adiabatic, kinetic contribution $\delta W_{\text{hot}} = -\frac{1}{2}\int d^3x d^3v\, L^{(1)*} f^{(1)}$ is defined by the perturbed Lagrangian of the particle motion in the drift approximation and the perturbed distribution function $f^{(1)}$ Ref. [3]. The growth rate is proportional to its imaginary part, i.e. $\gamma \propto \operatorname{Im}\{\delta W_{\text{hot}}\}$. Here $L^{(1)} = -(mv_\parallel^2 - \mu B)\, \vec{\xi} \cdot \vec{\kappa} + \mu B\, \nabla \cdot \vec{\xi} \approx -(mv_\parallel^2 + \mu B)\, \vec{\xi} \cdot \vec{\kappa}$, where $\vec{\kappa}$ denotes the curvature of the magnetic field and $\vec{\xi}$ the MHD perturbation. It holds that $\tilde{L}^{(1)} = \hat{L}^{(1)} \exp\left(-\; i n^\circ \varphi^{(\sim)}\right)$ is periodic in τ. Therefore, a Fourier expansion is possible $\tilde{L}^{(1)}(\tau) = \sum_{-\infty}^{\infty}{}_p\, Y_p\left(E,\ \mu,\ P_\varphi;\ \sigma\right) \exp\left(-\; i p \omega_b \tau\right)$, where $\omega_b \equiv 2\pi / \tau_b$. The Fourier coefficients are defined as $Y_p\left(E,\ \mu,\ P_\varphi;\ \sigma\right) = \oint \frac{d\tau}{\tau_b}\, \tilde{L}^{(1)} \exp\left(i p \omega_b \tau\right)$. Integration over the gyro angle and poloidal angle leads to

$$\delta W_{hot} = -\frac{2\pi^2 c}{Zem^2}\int\sum_{\sigma} dP_{\varphi} dE d\mu \tau_b \left(\omega - n^{\circ}\omega_*\right)\frac{\partial F}{\partial E}\sum_{p}^{\infty} \frac{\left|Y_p\right|^2}{\omega + n^{\circ}\langle\dot{\varphi}\rangle + p\omega_b}. \tag{1}$$

Resonaces appear for $\omega + n^0\langle\dot{\varphi}\rangle + p\omega_b = 0$. The equilibrium distribution function $F = f^{(o)}$ is a function of the adiabatic invariants, i.e. $F = F\left(E, \ \mu, \ P_{\varphi}\right)$.

In order to enable a fast analysis of JET discharges several approximations are introduced in form of a analytic, small-orbit approximation and a local treatment on a flux surface. The evaluation of δW_{hot} requires still the calculation of the bounce-average Fourier components, Y_p and the sum of the resonant contributions integrated over $\Lambda = \mu B_o/E$.

In the case of passing particles good agreement with the results of Betti and Freidberg, [4], is found as shown in Fig. 1. For RF heated JET discharges the fast particle distribution is modelled by a slowing down distribution, Fig. 2, and by the Stix approximation $f_h^{(0)} = \exp\left(-\frac{E}{T_{eff}}\left(1 + H\left(\frac{E}{E_j}\right)\right)\right)$ [5], Fig. 3. The results for deeply trapped particles, i.e. $\Lambda = 1$, and for on-axis heated particles, i.e. $\Lambda = 1\text{-}\varepsilon$, are displayed in the figures.

CONCLUSIONS

RF Heating provides interesting schemes to: i) excite TAE directly by nonlinear wave-wave drive and ii) generate sufficiently many energetic ions to destabilise the TAE, i.e wave-particle drive.

The stability analysis shows that it is possible to destabilise TAE modes in JET discharges via particle resonances for relatively low $\beta_{hot} \sim 10^{-4}$ in low density plasmas, $n_e \sim 10^{19}$ m^{-3}, if ions with very high energy (≥ 1 MeV) are generated by RF heating. These results are in qualitative agreement with the reported observation of TAE activity in JET [6]. It is emphasised that improved high-frequency diagnostics will enable more detailed comparison between theory and experiments.

Utilising the high-accuracy detection installed for the saddle coils excitation, i.e. frequency sweeping, synchronous detection and measurement of the plasma response, allows for accurate, independent determination of the damping effects and the destabilisation.

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STABILITY DIAGRAMS

Local stability analysis of TAE modes with n=3, m=3,4 localised at q=7/6, as a function of β_{hot} for the following plasma parameters: Te=Ti=10 Kev, E_{hot}= 1->3 Mev, B_T=2.8 T, $n_e=n_i=10^{19}m^{-3}$ at V_α/V_A=1. Different values of V_α/V_A are scanned by changing the density n_e and keeping the magnetic field constant.

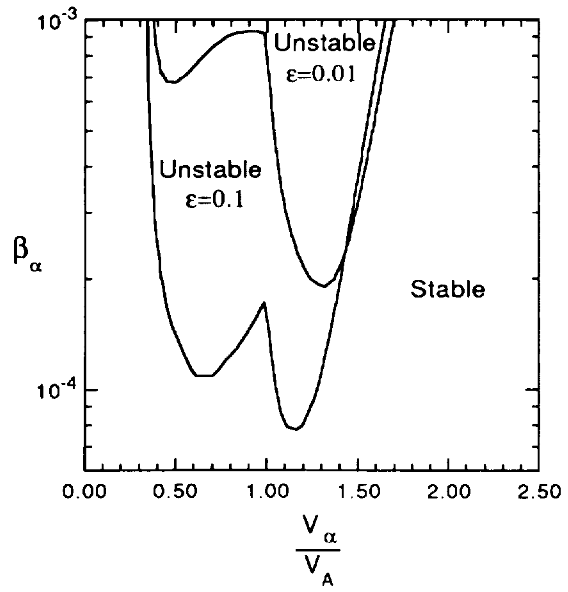

Figure 1 Isotropic slowing down distribution for particles with the birth energy of 3.5 MeV

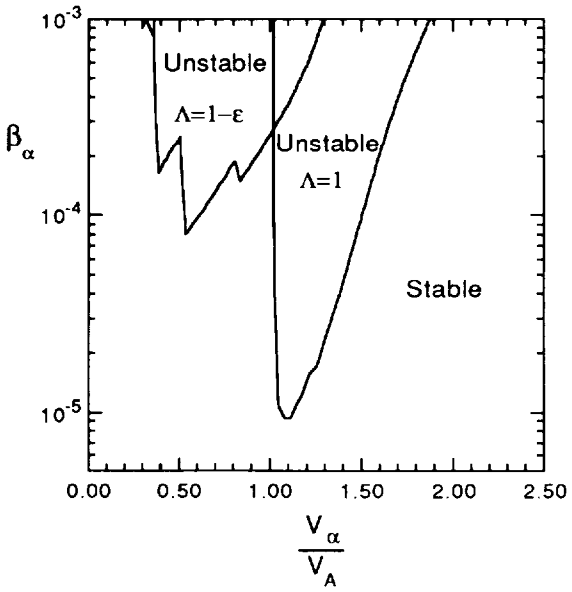

Figure 2 Anisotropic slowing down distributions for different pitch angles

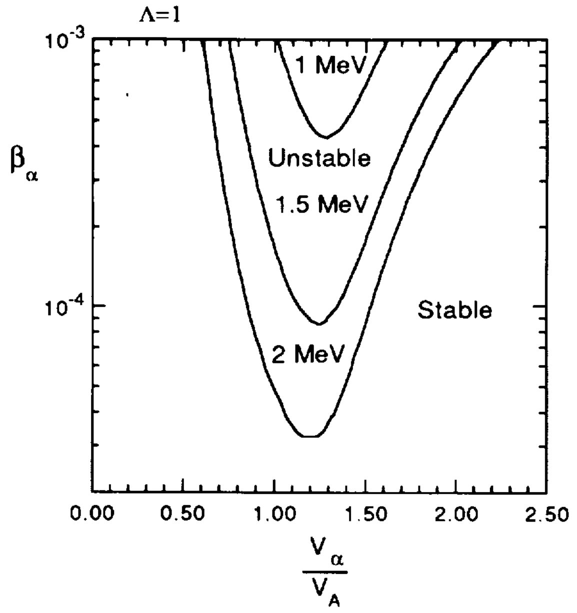

Figure 3a Stix distribution function for deeply trapped particles

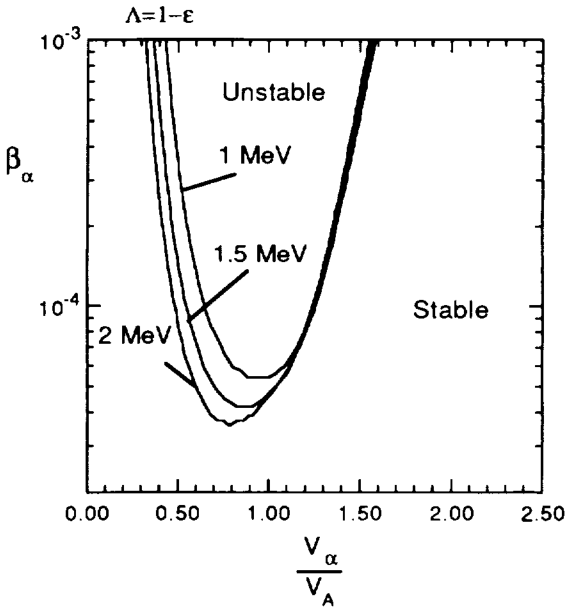

Figure 3b Stix distribution function for on-axis heated trapped particles