MHD Spectroscopy: Modelling the Excitation of TAE Modes by an External Antenna

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Introduction

Global Alfvén modes can be excited by energetic particles, in particular, by fusion born α particles. The destabilized modes can lead to an enhanced loss of confinement of the α particles, with the consequence that they are lost before being thermalized with the bulk plasma. Experimentally, the global Alfvén modes have been destabilized by the fast particles population created by neutral beam injection [1,2]. The damping of the modes was found to be an order of magnitude larger than the estimates based on electron Landau damping. Subsequently, new damping mechanisms have been proposed, i.e., continuum damping, ion Landau damping and electron kinetic (radiative) damping.

In JET, an experiment is planned to excite global Alfvén waves (TAE, EAE modes) by means of an external antenna. In contrast to previous experiments, the waves are not driven unstable but are oscillating with the frequency of the antenna. The saddle coils (see Fig. 1), which are newly installed in the JET vessel for disruption control will be used as the driving antenna. By scanning the driving frequency, the TAE and EAE modes will show up as resonances of the power absorbed by the plasma, as can be measured by the antenna impedance. The width of the resonance is directly proportional to the damping of the mode. In this way a direct measurement of the damping is obtained without the need to drive the global modes unstable, i.e. independent of the fast particle drive. Measuring the damping as a function of the fast particle population gives the possibility to study the fast particle drive.

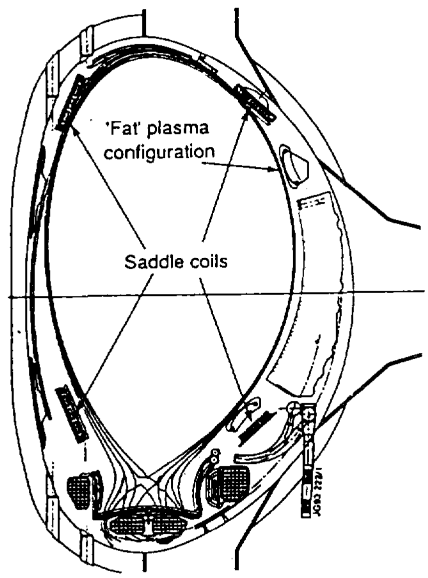

Fig. 1 *A cross section of the JET divertor geometry showing the poloidal position of the saddle coils. In the toroidal direction, there are four saddle coils both at the top and bottom of the vessel.*

Modelling the Excitation by an External Antenna

To model the excitation of the Alfvén waves, the plasma is described by the compressible resistive MHD equations in toroidal geometry. Since the amplitude of the excited waves will be small ($\delta B/B \sim 10^{-5}$) the linearized equations yield an appropriate description of the plasma oscillations. In the existing CASTOR [3] code the following equations have been implemented in toroidal geometry.

$$
(1)\quad
\begin{aligned}
\lambda\rho_1 &= -\nabla\cdot(\rho_0 \boldsymbol{v}_1)\\
\lambda\rho_0\boldsymbol{v}_1 &= -\nabla(\rho_0 T_1 + \rho_1 T_0) + (\nabla\times\boldsymbol{B}_0)\times(\nabla\times\boldsymbol{A}_1) - \boldsymbol{B}_0\times(\nabla\times\nabla\times\boldsymbol{A}_1)\\
\lambda\rho_0 T_1 &= -\rho_0\boldsymbol{v}_1\cdot\nabla T_0 - (\gamma-1)\rho_0 T_0\nabla\cdot\boldsymbol{v}_1 + 2\eta(\gamma-1)(\nabla\times\boldsymbol{B}_0)\cdot(\nabla\times\nabla\times\boldsymbol{A}_1)\\
\lambda\boldsymbol{A}_1 &= -\boldsymbol{B}_0\times\boldsymbol{v}_1 - \eta\nabla\times\nabla\times\boldsymbol{A}_1
\end{aligned}
$$

$\boldsymbol{v}_1, \boldsymbol{A}_1, \rho_1$ and T_1 are the perturbed velocity, vector potential, density and temperature, B_0, ρ_0 and T_0 are the equilibrium magnetic field, density and temperature, respectively. The ratio of the specific heats is given by γ. The time dependence is given by $u(\boldsymbol{r},t) = u(\boldsymbol{r})e^{\lambda t}$. Without the driver, λ is an eigenvalue of the eqs.(1). With the antenna, the stationary state solution is obtained in which all quantities oscillate with the driving frequency of the antenna: $Im(\lambda) = \omega_d$.

Modelling the excitation by the antenna requires a free boundary description of the plasma. The influence of the vacuum region between the plasma and an ideally conducting wall can be described by a relation between the normal and tangential components of the perturbed vacuum magnetic field at the plasma boundary [4].

$$
(\boldsymbol{b}\times\boldsymbol{n})_m = \sum_{\bar{m}} \alpha_{m,\bar{m}}(\boldsymbol{b}\cdot\boldsymbol{n})_{\bar{m}} + \beta_m^{ant}. \tag{2}
$$

here $\boldsymbol{n}$ is the unit vector normal of the plasma boundary, m and $\bar{m}$ are indices of the Fourier series in the poloidal angle. The vacuum response matrix, α, and the driving vector β_m result from two independent solutions of the vacuum equations $\nabla\cdot\boldsymbol{b}_v = 0$ and $\nabla\times\boldsymbol{b}_v = 0$ with b_v the vacuum magnetic field.

The matrix α is determined from the vacuum solution with $(\boldsymbol{b}\cdot\boldsymbol{n})_m = 1$ at the plasma boundary and $\boldsymbol{b}\cdot\boldsymbol{n} = 0$ at the wall. The antenna, situated on an arbitrary surface in the vacuum region, yields the additional term proportional to β_m^{ant}. This driving vector β is obtained from the solution with $\boldsymbol{b}\cdot\boldsymbol{n} = 0$ both on the wall and the plasma boundary and a jump in $(\boldsymbol{b}\times\boldsymbol{n})_m = j_m^{ant}$ at the antenna surface.

To reach a stationary state, some form of dissipation is needed. With a finite resistivity in the plasma, the Ohmic dissipation equals the power absorbed by the plasma.

Excited spectrum with JET saddle coils

The JET saddle coils consist of eight coils, four in the toroidal direction both at the top and bottom of the vessel. By switching the relative phases, toroidal mode numbers of $n = 1$ and 2 can be produced as the main harmonics. Other mode numbers will also be present as side bands. In CASTOR, the saddle coils are modelled as a sum of independent helical antennas with different toroidal mode numbers. The helical antenna preserves the localized nature of the antenna currents in the poloidal direction (see Fig. 1).

As an example, high performance discharge 26087 is analysed. This discharge has a toroidal beta of 2.5%, at about 80% of the Troyon limit. The continuum frequencies of this discharge, obtained with the CSCAS code [5], are plotted in Fig. 2. At this high value of the pressure, the slow continua, which are linear in the local pressure and

γ, overlap the Alfvén continuum. The interaction of the slow and the Alfvén continua breaks up the lowest Alfvén continuum and the separation between the slow and Alfvén branches disappears. In addition, slow continua exist within the lowest Alfvén gap. Due to the interaction of the slow and Alfvén branches a new gap opens up around $\omega/\omega_a = 0.20$. The ellipticity induced Alfvén gap is not affected by the slow modes.

This discharge is now, numerically, excited with the saddle coils as the external antenna in the $n = 1$ configuration. The complete spectrum of the plasma response due to the predominantly $m/n = 2/1$ magnetic field perturbation induced by the antenna is shown in Fig. 3. The toroidal Alfvén eigenmodes (TAE) have the frequencies $\omega = 0.35, 0.40$ and 0.72. The TAE mode at $\omega = 0.35$ lies on the edge of the lower 'Alfvén' continuum and is heavily damped. In the case of an incompressible plasma, i.e. no interaction of Alfvén and slow modes, the TAE gap is completely open and the TAE mode at $\omega = 0.40$ experiences no continuum damping. In a compressible plasma, the mode interacts with the slow/Alfvén continuum and does have singularities. However, the continuum damping due to these singularities is small ($< 2 \times 10^{-3}$). This is due to the parallel polarization of slow continuum modes for which continuum damping is much less efficient. From this, it is clear that almost undamped TAE modes can still exist in relevant discharges at a pressure close to the Troyon limit.

Above $\omega = 0.75$ the second Alfvén continuum sets in. This causes the increased background in the absorbed power up to $\omega = 0.97$. The large peaks between $\omega = 1.0$ and 1.35 are due to ellipticity induced eigenmodes (EAE). Above $\omega = 1.35$ the third Alfvén continuum exists.

In the lowest, pressure induced, gap, we find a sharp resonance at $\omega = 0.22$.This resonance is due to a global mode inside the gap of the $m = 2$ slow and $m = 1$ Alfvén gap, i.e., the global mode has a large $m = 1$ and $m = 2$ component. This resonance disappears if the plasma is incompressible. A similar, pressure driven, mode has been found in [2], where it is called a BAE mode for beta induced Alfvén eigenmode. The mode at $\omega = 0.22$ is, however, not a clear Alfvén mode. The influence of the slow continuum is clearly seen in the polarization of the mode. The ratio of the parallel to perpendicular component of the displacement is a factor of 10 larger than that of the pure Alfvén mode at $\omega = 0.40$. The continuum damping of this mode is small. However, at these relatively low frequencies, the contribution of ion Landau damping is expected to become dominant. Therefore, this global mode is not expected to be relevant with respect to α-particle instabilities.

Conclusion

The plasma response induced by the JET saddle coils as the external antenna can be calculated accurately for general JET discharges, providing a clear example of what has been termed 'MHD spectroscopy' [6]. Peaks in the antenna impedance (the power absorbed by the plasma) as a function of the driving frequency indicate global modes, the width of these peaks yields the damping. This method allows finite pressure, i.e. the influence of the slow continua, to be included consistently. In contrast, the method based on the normal mode analysis has great difficulty finding the interesting eigenmodes in the case of overlapping slow/Alfvén continua.

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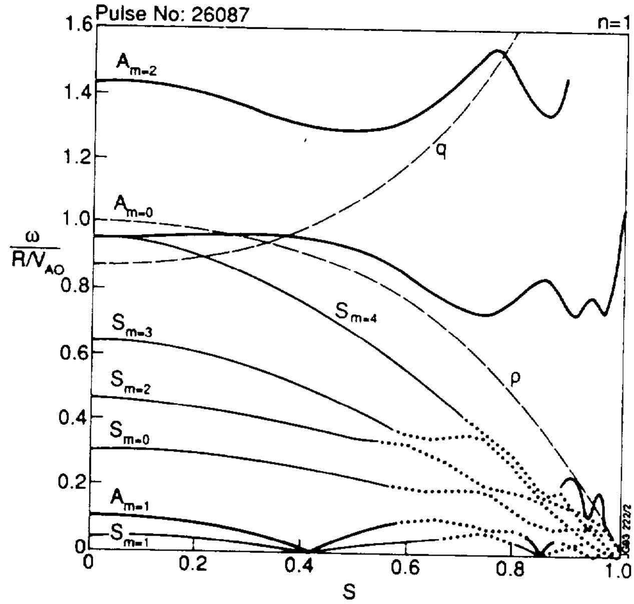

Fig. 2 *The slow (thin lines) and Alfvén (fat lines) continua as a function of the radial coordinate* $s = \sqrt{\psi}$ *of JET discharge 26087. The q-profile and the density profile are also drawn. The index to the slow (S) and Alfvén (A) continua indicates the main poloidal harmonic. The dotted lines represent the continua with a strong interaction between Alfvén and slow branches.*

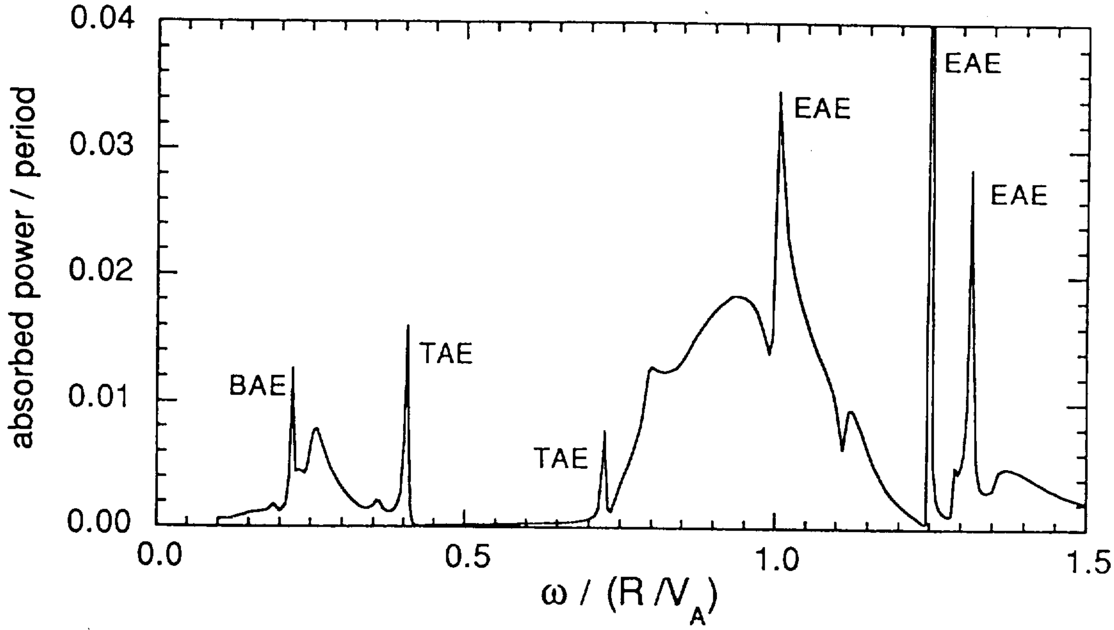

Fig. 3 *The power absorbed by the plasma as a function of the antenna frequency. The Alfvén frequency is 332 kHz. The plasma resistivity* η *is* 10^{-7}, *the toroidal mode number* $n = 1$.