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Journal
Physics of Plasmas, 5(8)

ISSN
1070-664X

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Publication Date
1998

DOI
10.1063/1.873019

Prediction of Alfvén eigenmode dampings in the Joint European Torus

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(Received 3 February 1998; accepted 13 May 1998)

Predictions from a gyrokinetic toroidal plasma model reproduce for the first time the evolution of Alfvén eigenmode (AE) dampings over a range of discharges. The coupling between shear-and kinetic-Alfvén waves is responsible for the main source of damping through Landau interactions and can be an order of magnitude larger than fluid predictions neglecting global kinetic effects. Strong stabilization occurs when the wave field gets localized radially by a rise in the edge magnetic shear, explaining why global AEs have never been detected in the Joint European Torus [Rebut, Bickerton, and Keen, Nucl. Fusion **25**, 1011 (1985)] in the presence of an X point and suggesting how global Alfvén instabilities could be avoided in future reactors. © *1998 American Institute of Physics.* [S1070-664X(98)02508-7]

I. INTRODUCTION

Whether global modes of the Alfvén wave driven by fusion-born α particles are stable is a critical issue for fusion devices such as the International Thermonuclear Experimental Reactor (ITER).[1] The growth rate of the instability depends on the strength of the α-particle pressure gradient drive, which has to remain smaller than the overall damping from the collisions and the resonant Landau interactions between the particles and the wave field. Because the predictions are very sensitive to the spatial structure of the eigenmode which in turn depends on the equilibrium profiles, magnetohydrodynamic (MHD) models have been developed assimilating the bulk plasma with an ideal or resistive fluid.[2–7] Growth rates may then be evaluated approximately from the shear-Alfvén wave field with simplified models including direct Landau damping,[8,7] continuum damping,[9–11] and radiative damping.[12] Even if the theoretical calculations[7,13] performed in this manner could only occasionally explain the observed instability thresholds when the mode coupling to kinetic waves did not affect the eigenmode structure, it is remarkable how the theoretical understanding of the beam Landau damping[14] paved the way for the first observation of α-particle driven toroidicity Alfvén eigenmodes (TAEs).[15]

II. MODELING

A proper evaluation of the growth rate requires taking into account the finite ion gyroradius responsible for the mode conversion from fast to slow waves such as the kinetic-Alfvén[16] and the drift waves. This generally occurs when the spatial scale of two waves match at a resonance, but can also be induced through mode coupling by the magnetic field curvature[17,18] and, as will be shown below, by the weak magnetic shear in the plasma core. In the studies below, the gyrokinetic predictions are found to agree with the measured frequencies and damping rates[19] over a range of discharges and times, this in contrast with computed damping rates that are an order of magnitude smaller when global kinetic effects are neglected. Apart from quantifying for the first time the relative importance of what could be associated in simplified models with continuum and radiative damping, the results illustrate that when the central magnetic shear $\hat{s}=(\rho/q)(\partial q/\partial\rho)$ is smaller than $\epsilon=\rho/R$ the inverse aspect ratio, there can be a dramatic change in the AE structure due to mode conversion to the kinetic-Alfvén wave, which strongly enhances the Landau absorption in the plasma core. The calculations also show the stabilizing effect of a high magnetic shear at the plasma edge, giving a plausible explanation why antenna excited (global) Alfvén eigenmodes (AEs) have never been observed in Joint European Torus (JET) X-point configurations. To our knowledge, this study is the most detailed comparison which has been undertaken between a nonideal MHD spectrum and experimental measurements; it also provides a strong validity check for the ITER predictions, showing that in a reference equilibrium, AEs with low to intermediate toroidal mode numbers $n=1-12$ are stable for a large variety of burn conditions.[20]

Having chosen a discharge with good damping measurements, the equilibrium magnetic field, the density, and temperature profiles have been reconstructed with the best possible fit to the experimental diagnostics.[21,22] The gyrokinetic toroidal PENN code[23] is then used to predict the spectrum from the equilibrium data only, monitoring the response peaks in the same manner as in the experiment (Ref. 19) to determine the frequency and damping of AEs that are sufficiently global to reach the saddle coil antenna at the bottom of the plasma. The plasma model[24] is based on a finite Lar-

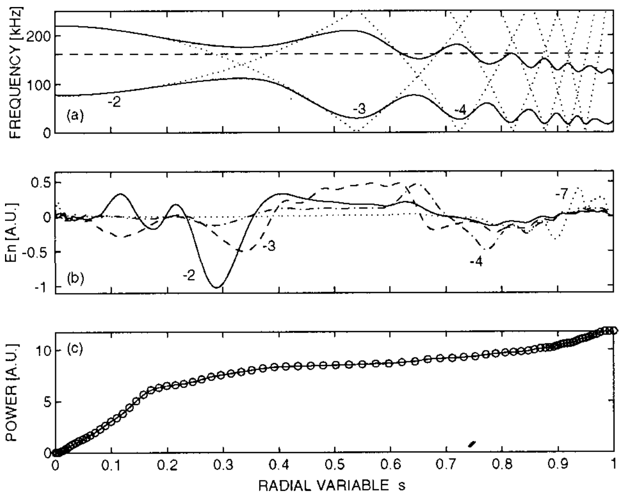

FIG. 1. AE mode $n=2$ at 161 kHz in the discharge No. 31561 at 10 s with parameters $B_T=1.65$ T, $q_0=1.13$, $q_a=5.49$, $n_e(0)=n_D(0)=1.6\times10^{19}$ m^{-3}, $T_e(0)=T_D(0)=2$ keV. The plots show a sketch of the shear Alfvén spectrum with a dashed line for the global AE frequency (a), the Fourier components of the radial electric field $\Re e(E_n)$ in (b) and $P(s)$ the power absorption integrated from the center (c), with circles identifying the radial discretization as a function of the normalized radius s.

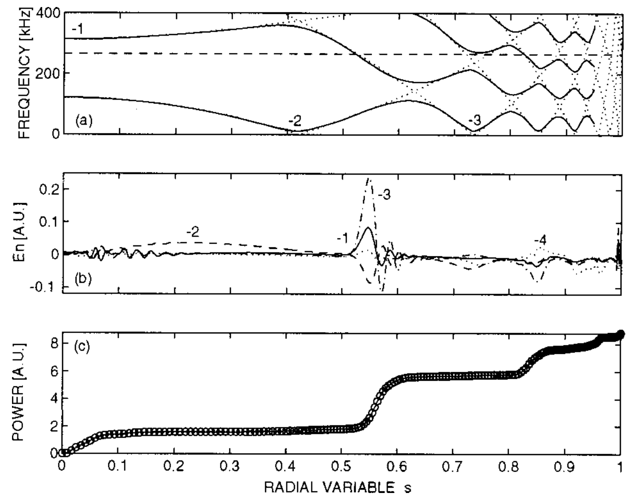

FIG. 2. AE mode $n=2$ at 266 kHz in the discharge No. 33273 at 16.35 s with parameters $B_T=3.1$ T, $q_0=0.86$, $q_a=4.46$, $n_e(0)=n_D(0)=4.48\times10^{19}$ m^{-3}, $T_e(0)=T_D(0)=2$ keV. The same type of plots as in Fig. 1.

mor radius expansion for the passing bulk particles and takes into account the magnetic and diamagnetic drifts induced by the equilibrium inhomogeneities. Resonant wave–particle interactions are modeled with an approximate functional dependence for the parallel wave vector $k_\parallel=n/R$, where n is the toroidal mode number and R the major radius, justified by an iterative evaluation of $k_\parallel$ from the wave field along the same lines as in Ref. 23. The PENN code has been successfully tested for heating scenarios from the ion-Bernstein[25] down to the Alfvén range of frequencies,[23] and has been validated for lower frequencies with measurements of the AE spectrum[26] and eigenmode structures[27] in the JET tokamak.

III. ANALYSIS

The first discharge being analyzed (No. 31561 at 10 s) is an ohmic fat pear-shaped plasma with a weak magnetic shear $\hat{s}<\epsilon$ from the core out to a normalized radius $s=\sqrt{\psi}\simeq0.18$, where ψ stands for the poloidal magnetic flux. The safety factor $q(s)$ rises rapidly toward the edge so that a multitude of gaps appears in Fig. 1(a) by the coupling of neighboring poloidal Fourier harmonics $m=-2,...,-10$. The misalignment of individual gap frequencies (which decrease with the deuterium density n_D as $1/q\sqrt{n_\mathrm{D}}$ when moving radially outward) formally closes the global gap in the fluid spectrum, so that an Alfvén resonance remains in the plasma for all frequencies. Scanning the interval [120;180] kHz, an $n=2$ AE is predicted at 161 kHz with a damping rate of $\gamma/\omega_\mathrm{pred}=0.013\pm0.003$, where the uncertainty refers to oscillations in the numerical convergence. A single $n=2$ eigenmode is also observed in the experiment with a frequency of 131 kHz which is somewhat lower, probably because of the uncertainty on the safety factor in the core which is larger when no sawtooth inversion radius can be used as a diagnostic; the damping rate $\gamma/\omega_\mathrm{exp}=0.0146$ is, however, in very good agreement with the predicted value. Figure 1(b) shows that the mode has a global radial extension; the toroidicity induced variation of the shear-Alfvén wave field matches the kinetic-Alfvén wavelength in the $(-2,-3)$ TAE gap and creates standing wave between the mode coupling region around $s=0.35$ and the plasma core.[17] The electric field component parallel to the magnetic field $E_\parallel$ gives rise to an electron Landau damping which can be partitioned with the integrated power $P(s)=\int_0^s P(s')ds'$ in Fig. 1 (c) as follows: 70% absorbed by the kinetic-Alfvén wave induced in the core where no resonance is present, 5%–10% by mode conversion at Alfvén resonances ($s=0.62$, 0.68, 0.75), and the remaining 20%–25% by direct Landau damping of the shear-Alfvén wave field in the edge region, where the magnetic shear localizes the mode radially and thereby increases the absorption. From the wave field, it is clear that simplified models such as radiative damping and continuum damping are not applicable, the former because a standing kinetic wave is created in the core and the latter because the kinetic wavelength is comparable with the gap size. The global character of wave fields such as the one in Fig. 1(b) also explains why no correlation is observed in Fig. 5 of Ref. 27 between the high-n radiative damping model[12] and the AE damping measurements in JET.

The second discharge (No. 33273 at 16.35 s) is an elongated pear-shaped plasma which has been examined experimentally in Ref. 27. Two $n=2$ global AEs are predicted in the interval [100;300] kHz, one around 140 kHz with a weak antenna coupling and relatively large damping and a second with a 30 times better coupling at 266 kHz and a weak damping $\gamma/\omega_\mathrm{th}^\mathrm{EAE}=0.0026\pm0.0004$ depending rather sensitively on the magnetic shear. Two modes are also found in the experiment at 142 and 277 kHz; the first disappears in the sweep 1 s later, in agreement with the theoretical prediction of weak coupling for the lower frequency mode, while the damping measured for the second $\gamma/\omega_\mathrm{expt.}^\mathrm{EAE}=0.0014$ is a factor of 2 smaller than the experimental value. Figure 2 shows that 60% of the electron Landau absorption occurs through mode conversion at the Alfvén resonances ($s=0.52$, 0.83), another 20% by mode coupling in the weak magnetic shear region ($s<0.17$), and the remaining 20% by direct damping of the shear-Alfvén wave field in the edge where the magnetic shear is stronger. This global wave field with kinetic Alfvén waves damped in the vicinity of the conversion layers provides an example of experimental interest where the continuum damping $\gamma/\omega_{\rm fluid}^{\rm EAE}\sim 0.01$ calculated in Ref. 27 using a fluid plasma model can be very misleading.[11] A reason which may explain the overestimation of the electron Landau damping in our gyrokinetic calculation could be that we have neglected the reduction of the number of resonant electrons by the trapping in the toroidal magnetic field. This has been examined within a large aspect ratio expansion for the shear-Alfvén wave field only in Refs. 28 and 29, but would here require a fully toroidal (nonlocal) gyrokinetic calculation to take into account the coupling to the kinetic Alfvén wave. Studies carried out by varying the equilibrium parameters moreover show that when the damping is as small as $\gamma/\omega \simeq 0.001$, the theoretical result depends sensitively on the equilibrium profiles, so that a ~5% uncertainty in the safety factor can also account for a factor of 2 discrepancy in the damping.

A third series of predictions has been carried out for the discharge No. 38573 in which the evolution of an $n=1$ AE has been measured from its birth around 3 s when a $(-1,-2)$ TAE gap is formed around $q_0=1.5$ on the plasma axis, drifting first rapidly outward to $s\simeq 0.55$ at 4.7 s, the AE going through a nonresonant 80 keV beam heating phase between 5.5 and 7.5 s, until it again disappears after 10 s when an X point is formed at the bottom of the elliptical plasma and the safety factor in the core reaches a minimum of $q_0=0.92$. Two global kinetic Alfvén eigenmodes KAEs[17,26] are predicted in the interval [160;210] kHz, with wave fields that reflect the $l=0,1$ radial oscillations of the kinetic-Alfvén wave modulating the TAE wave field inside the $(-1,-2)$ gap.

Because the interval scanned experimentally is very small $\Delta\omega \simeq 3\gamma_{\rm expt.}$ and the antenna coupling to the higher frequency $l=0$ mode is predicted to be better until 4.7 s, only the high frequency KAE appears on the measurements. Figure 3 shows that the predicted AE frequencies fall within ~3% of the experimental measurements, reproducing well the variation from the beam fueling. The agreement achieved for the damping is around 30% for most of the discharge except in the beginning when the gap position varies very rapidly, making the predictions very sensitive to the mode conversion parameters in the plasma core. This is clearly apparent in the wave fields of Fig. 4, where the kinetic-Alfvén wave dominates the mode structure until 4.7 s. Most important however is that the largest fraction of the Landau damping from 4.0 to 8.4 s is here induced by short wavelength oscillations in the plasma core (Fig. 5): removing the kinetic effects artificially from the model for small radii ($s<0.2$) yields a fluid-like electron Landau damping rate from mainly the shear Alfvén wave $\gamma/\omega_{\rm art}\simeq 0.003$ which is an order of magnitude smaller than observed in the experiment. Since the gap opens up monotonically from $s\simeq 0.65$ to the center, this core-localized mode conversion has to be of different nature than the mode coupling induced inside the toroidicity gap.[17] Studies carried out by varying locally the central magnetic shear show that the oscillations are caused by an increase of the kinetic-Alfvén wavelength in the weak shear region, resulting in the mode conversion once the spatial scale of the kinetic-Alfvén wave matches the shear-Alfvén wave field scale length. Because of the complicated nature of this mechanism, we believe that it is not possible to derive a simplified model that fits well the global AE measurements. Instead, we use here the predictions from the comprehensive PENN model to illustrate the phenomenon and show not only that it is important, but that it is also in agreement with the measurements. Another effect apparent in

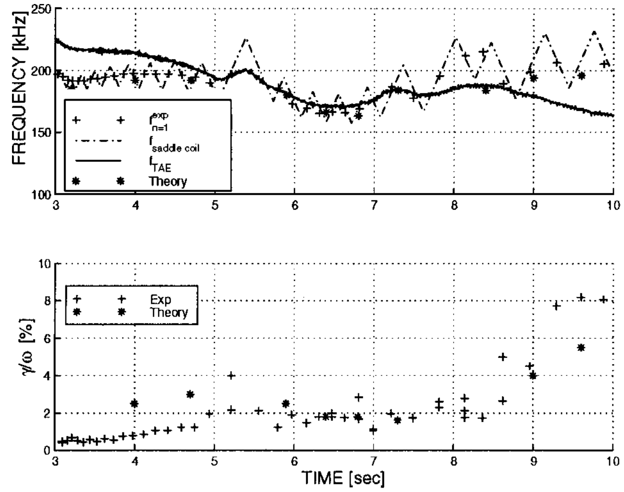

FIG. 3. Comparison between the $n=1$ AE frequencies (top) and dampings (bottom) *predicted* (*) and measured (+) during the evolution in the discharge No. 38573. Experimentally, the systematic error from the choice of the relevant diagnostic channels to fit is the dominant source of uncertainty (~10%–30% for γ/ω); for the theory the uncertainty comes mainly from the reconstruction of the safety factor profile (~10%–20% for q_0). Parameters at 4.0 s are $B_T=2.56$ T, $q_0=1.36$, $q_a=4.62$, $n_e(0)=n_{\rm D}(0)=1.75\times 10^{19}$ m^{-3}, $T_e(0)=2.62$ keV, $T_{\rm D}(0)=1.97$ keV.

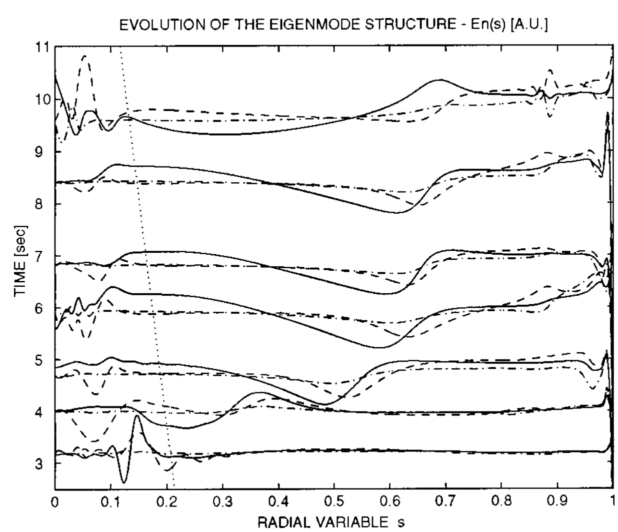

FIG. 4. Evolution of the theoretical eigenmode structure $\Re e(E_n)$ in the discharge No. 38573. The dotted line locates the weak shear region in the core where $\hat{s}=\epsilon$.

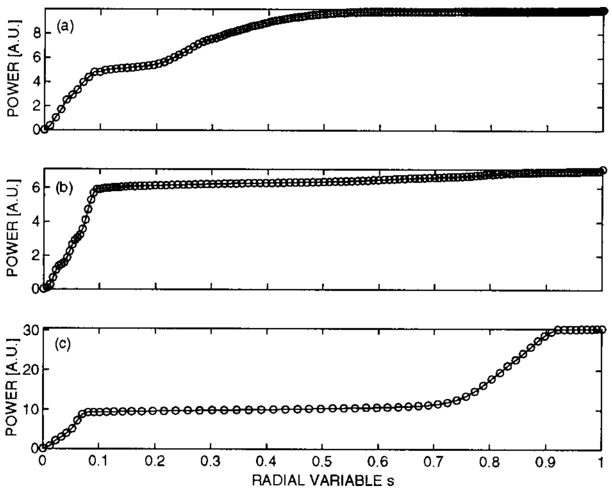

FIG. 5. Power absorption integrated from the center $P(s)$ in the discharge No. 38573 just after the TAE appears in the plasma core at 4.0 s (a), during the neutral beam heating at 6.4 s (b), and immediately before the formation of an X point at 9.6 s (c).

Figs. 3–5 which becomes dominant after ~8 s, is the enhanced global damping rate due to the radial localization of the shear-Alfvén wave field in the edge region. It is caused by the rise of the edge magnetic shear when the plasma gets diverted, explaining why antenna excited AEs have never been observed in JET in the presence of X points.

IV. CONCLUSION

In summary, gyrokinetic calculations of global AE dampings predicted for JET plasmas are in good agreement with the measurements and the uncertainties obtained from these studies show to which extent predictions are possible for ITER. Resonant Landau interaction with the global shear- and kinetic-Alfvén wave field provide for the dominant damping mechanism, with mode conversion induced by Alfvén resonances, toroidal mode coupling, and the weak magnetic shear in the plasma core.

ACKNOWLEDGMENTS

Help from D. Borba, W. Zwingmann, O. Sauter for the equilibrium reconstruction, P. Lavanchy for the experimental support, and useful discussions with T. Hellsten, J. Vaclavik, and L. Villard are gratefully acknowledged. This work was supported in part by the Swedish (A.J.), the Swiss (A.F.) National Science Foundations, and Subcontract No. SC-L134501 to the U.S. Department of Energy Contract No. DE-AC03-89ER51114 (W.W.H.). The experiments have been carried out within a JET/CRPP task agreement and the calculations performed on the CRAY C-94 super-computer in Linköping and the NEC SX-4 in Manno.

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