# On Resonance Absorption and Continuum Damping

A. Jaun[1,2], K. Appert[1], T. Hellsten[2], J. Vaclavik[1], L. Villard[1]

[1] CRPP-EPFL, Association EURATOM-Confédération Suisse, CH-1015 Lausanne, Switzerland

[2] Alfvén Laboratory, EURATOM-NFR Association, KTH, SE-100 44 Stockholm, Sweden

ABSTRACT. The absorption of power is studied with fluid and gyrokinetic plasma models, when two Alfvén or ion-ion hybrid resonances provide for a weak damping in a partially standing wavefield. Examples chosen in slab and toroidal geometry show that the the fluid predictions based on resonance absorption are generally very different from the Landau damping of mode-converted slow waves. They in particular suggest that the continuum damping of toroidal Alfvén eigenmodes (TAE) and the power deposition profiles obtained in the ion-cyclotron range of frequencies (ICRF) using fluid plasma models are very misleading.

PACS numbers: 52.35.Bj, 52.35.Py, 52.50.Gj, 52.65.Tt

Ever since Landau's lesson, which lead to the discovery of the damping associated with the wave-particles resonance, it has been recognized that the integration over time of partial differential equation singularities requires a careful treatment that guarantees in effect that the causality remains preserved. By analogy, when the fluid wave equations are integrated in presence of an Alfvén or ion-ion hybrid resonance, a residual absorption of power appears which may be evaluated either by taking into account an arbitrarily small dissipation of the plasma or by adding artificially an imaginary part to the frequency. Studying the propagation of the fast-magnetosonic wave in the ion-cyclotron range of frequencies (ICRF), Budden [1] for example determined the fraction of the power absorbed, transmitted and reflected by a resonance-cutoff pair using a fluid plasma model, without specifying the mechanism actually responsible for the power dissipation.

If the plasma temperature is sufficiently large, the resonant layers where the fluid equations are singular coincide with the location where the fast wave energy can be converted to slow kinetic waves owing their existence to the finite Larmor radius (FLR) excursion of the ions [2]. The change of polarization accompanied with a rise in the electric field component parallel to the magnetic field is then generally responsible for the power dissipation, with resonant wave-particle interactions that occur as the slow wave propagates away from the conversion layer. Using an FLR expansion [3, 4, 5] and solving the full non-local problem [6], it has been found that the total power converted from a fast wave traveling in a single pass through a resonance depends only weakly on the slow wave parameters; the resonance absorption from fluid plasma models then coincides to a good degree of accuracy with the Landau damping of the slow wave described by the gyrokinetic models.

The aim of this letter is to draw attention to the fact that this is not in general true when two resonances are present in the same global wavefield, this even when the slow wave is damped in the vicinity of the mode conversion surface. In particular, the continuum damping of Alfvén eigenmodes (AE) [7, 8] and the resonance absorption of ICRF driven wavefields calculated with toroidal fluid plasma models [9, 10] are shown to be dramatically different from our gyrokinetic calculations, suggesting that AE mode stability threshold and ICRF power deposition profile predictions are very questionable when using fluid models.

To illustrate the concept first in a simple shearless slab plasma, Fig.1 shows an Alfvén wave heating scenario similar to the TCA tokamak [11] ($B_0$=1.5 T, $n_{e,0} = 2.3\times 10^{19}$ m$^{-3}$, $T_{D,0}$=350 eV, $f_{ant} = 2$ MHz, $k_y = -5$ m$^{-1}$, $k_z = 2.9$ m$^{-1}$). An antenna current is imposed in the vacuum region on the right ($x = x_a = +19$ cm) and launches an evanescent fast wave into the plasma ($|x| < x_p = 18$ cm). After reflections, a global wavefield is created oscillating in phase in the entire cavity bounded by perfectly conducting walls ($|x| = x_w = 21$ cm). A parabolic variation of the density $n_e(x) = n_D(x) = n_{e,0}[1 - 0.95(x/x_p)^2]$ generates two Alfvén resonances at $|x| = x_r = 9.2$ cm, which are set to electron temperatures that differ

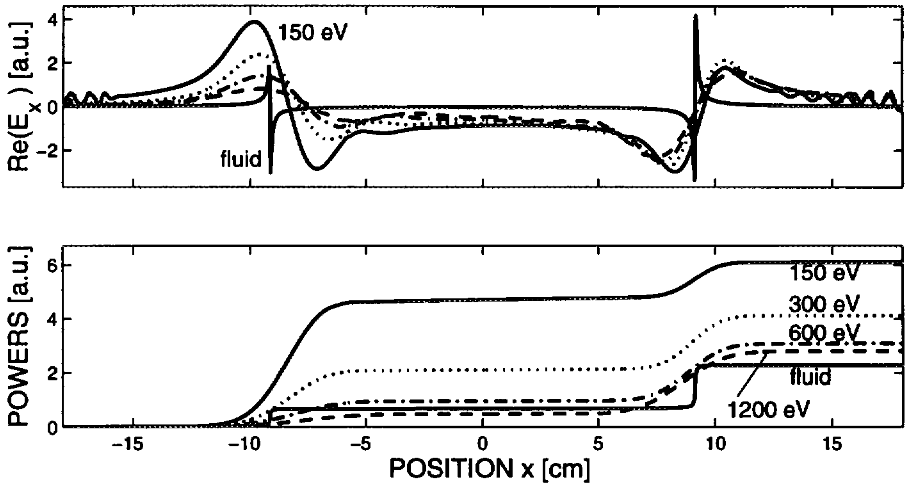


Figure 1: Alfvén wave heating scenario in a TCA-like slab plasma driven with an antenna from the right. The wavefield $Re(E_x)$ (top) and the integrated power $P(x)$ (bottom) calculated using a fluid model are compared with their gyrokinetic counterparts obtained for a rising temperature $T_{e,0}$ = 150, 300, 600, 1200 eV. The conversion layers are set to temperatures that differ by more than a factor two with an asymmetric profile of the form $T_e(x) = T_{e,0}[1 - 0.95(x/18)^2]^2[1 - 0.5(x/18)]^2$.

by more than a factor two $T_e(x) = T_{e,0}[1 - 0.95(x/x_p)^2]^2[1 - 0.5(x/x_p)]^2$, keeping that of the deuterons equal on both sides $T_D(x) = T_{D,0}[1 - 0.95(x/x_p)^2]^2$ eV. Using the full wave code ISMENE [12, 13] to compute the perpendicular wavefield $(E_x, E_y)$ with a cold-fluid plasma model (see Ref.[13], eqs.6.1-6.2), sharp variations appear at the resonances which have been numerically resolved in Fig.1(top) by adding a small imaginary part $\delta = 0.02$ to the antenna frequency $\omega = 2\pi f_{ant}(1 + i\delta)$. Apart from details in the vicinity of the resonant layers, a change of the artificial damping $\delta \in [0.002; 0.02]$ does neither affect the integrated power $P(x) = \int_{-x_p}^{x} Im[\frac{\omega}{8\pi} Im(\mathrm{E}^* \cdot \epsilon \cdot \mathrm{E})]dx'$ in Fig.1(bottom) nor does it modify the relative power fraction absorbed at each resonance (table 1, fluid), suggesting that the power resonantly absorbed does not depend on the manner how the equations are regularized.

This fluid calculation has now to be contrasted with the gyrokinetic results from the same code, when all the wavefield components $(E_x, E_y, E_z)$ are solved in terms of a second order FLR expansion of the plasma dielectric tensor (see Ref.[13], eqs.6.17-6.20). Fig.1(top) shows that a mode-converted kinetic Alfvén wave (KAW) propagates inwards from both sides and gets immediately damped by Landau interactions with the electrons in the neighborhood of the conversion layer. The short wavelength oscillations in the edge region ($|x| > 12$ cm) come from the surface quasi-electrostatic wave (SQEW) which is directly excited at the plasma boundary, but is unimportant for the subsequent analysis. Rising the electron temperature in the center $T_{e,0} = 150, 300, 600, 1200$ eV while keeping that of the ions fixed, Fig.1(bottom) shows that the integrated power profile $P(x)$ is changing: not only the total power absorption is mod-

| $T_{e,0}$ [eV] | $f^{left}_{x=-x_r}$ [%] | $f^{right}_{x=+x_r}$ [%] |
|---|---|---|
| 150 | 78 | 22 |
| 300 | 51 | 49 |
| 600 | 44 | 56 |
| 1200 | 17 | 83 |
| fluid model | 30 | 70 |

Table 1: Fraction of the power absorbed by each resonance, based on the fluid and gyrokinetic power deposition profiles in Fig.1(bottom)

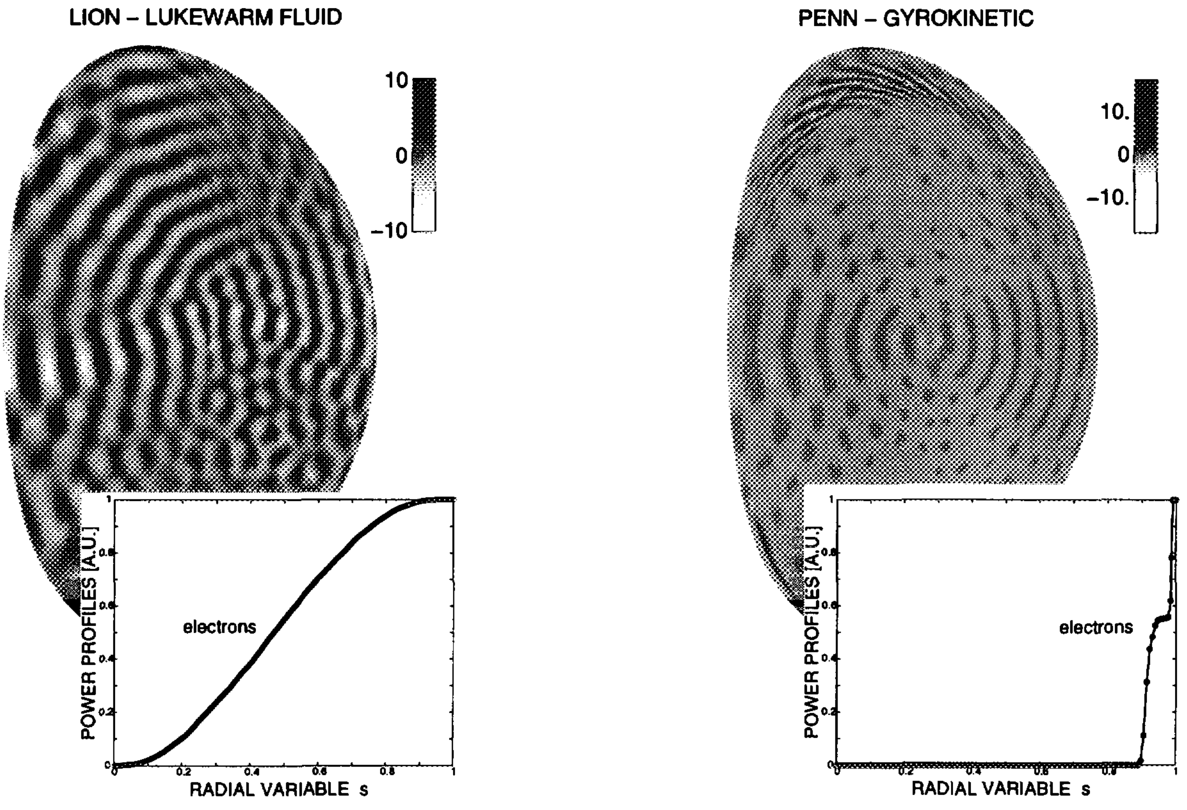


Figure 2: Current drive scenario proposed in Ref.[17] for ITER. The global wavefield $Re(E_n)$ (top) and the integrated power profile $P(s)$ (bottom) both show that the mode-conversion predicted by the gyrokinetic PENN calculation (right) is not reproduced with resonance absorption in the fluid LION code (left), suggesting that fluid predictions can be very misleading.

ified, but also the fraction absorbed by each resonance is dramatically different (table 1). This strong dependence on the temperature is of course not reproduced with the fluid plasma model and is in apparent contradiction with the small dependence on the slow wave parameters which has previously been observed in other comparisons. The paradox is solved by realizing that a small change in the "single pass" mode-conversion efficiency, which is rendered visible because of the temperature asymmetry, is here strongly amplified when the global wavefield carries fast wave energy from one resonance to the other.

This phenomenon, which has for simplicity been illustrated with the simple slab calculation above, becomes particularly important in tokamaks and stellarators where the magnetic curvature and the finite frequency in the ion-cyclotron range couple different poloidal and toroidal harmonics, forming global modes which can interact with resonant surfaces throughout the plasma radius. Alfvén eigenmodes get damped by resonances, but the continuum damping predicted using fluid plasma models [7, 8] sometimes disagrees by an order of magnitude with the gyrokinetic predictions and the experimental measurements [14, 15]. ICRF heating scenarii generally involve a multitude of resonances with large poloidal mode numbers $|m| > 20$. Global fluid calculations suggest that they are generally not excited because the geometrical coupling is very weak for low antenna mode numbers $|m_{ant}| \sim 5$. The gyrokinetic calculations from Ref.[16] however show that large poloidal mode numbers appear because of the toroidicity, when the fast and KAW wavelengths match at a resonance $\vec{k}_{fast} = \vec{k}_{slow}$ where the thermal electron velocity exceeds the parallel wave phase velocity $\omega/(k_{\|}v_{th,e}) < 1$.

The second example illustrates this in Fig.2 with a current-drive scenario proposed in Ref.[17] for the international thermonuclear experimental reactor (ITER) ($B_0$=6 T, $q_0 = 1.03$, $\beta_{tor} = 2.7\%$, $n_{e,0} = 1.4 n_{D,0} = 3.5 n_{T,0} = 1.4 \times 10^{20}$ m$^{-3}$, $T_{e,0} = T_{D,0} = T_{T,0} = 19$ keV, $f_{ant} = 20$ MHz, $n_{tor} = 21$). The lukewarm fluid LION code [9] calculation in Fig.2(left) suggests that the fast wave emmitted by an antenna on the low magnetic field side of the torus, first propagates inwards past the magnetic axis and forms a partially standing global wavefield that extends throughout the torus. The coupling to high poloidal mode numbers is however sufficiently weak that the resonance absorption remains negligible and the power gets almost homogeneously absorbed by the fast wave electron Landau damping and transit-time magnetic pumping (TTMP). This fluid prediction is dramatically different from the gyrokinetic result obtained from the PENN code [16], which shows that strong mode-conversion takes place where the partially standing fast wavefield meets the KAW scalelength in the neighbourhood of fluid resonances with large poloidal mode numbers $m \simeq 25$. The power is then mainly deposited by the electron Landau damping of the KAW, in the plasma edge region where the resonance absorption computed with fluid plasma models remains negligible. Apart form questioning the validity of fluid plasma models for weak absorption, this mode-conversion at the plasma edge provides for a plausible mechanism explaning the degradation in the heating efficiency which has been observed in the experiments [18].

In summary, both examples chosen above in slab and toroidal geometry show that fluid plasma models cannot be used to correctly predict the power absorption and the continuum damping when two resonances or more are present in a partially standing wavefield. This is in particular true for the prediction of Alfvén eigenmode dampings and the modeling of the power deposition profiles during ICRH, where more sophisticated gyrokinetic descriptions are required - at least.

One of the authors (A.J.) acknowledges useful discussions with F. Zonca. This work was supported in part by the Swiss and the Swedish National Science Foundations and the calculations were performed on the CRAY C-94 super-computer in Linköping.

## References

[1] K. Budden, *Radio Waves in the Ionosphere*, Cambridge University Press (1985) 596

[2] A. Hasegawa, L. Chen, Phys. Rev. Lett. **35** (1975) 370

[3] D.G. Swanson, Phys. Fluids **24** (1981) 2035

[4] P. Colestock, R. Kashuba, Nucl. Fusion **23** (1983) 763

[5] J.A. Heikkinen, T. Hellsten, M.J. Alva, Nucl. Fusion **31** (1991) 417

[6] O. Sauter, J. Vaclavik, Comput. Phys. Commun **84** (1994) 226

[7] M. N. Rosenbluth, H.L. Berk, J.W. Van Dam, D.M. Linberg, Phys. Rev. Lett. **68** (1992) 596

[8] F. Zonca, L. Chen, Phys. Rev. Lett. **68** (1992) 592

[9] L. Villard, K.Appert, R.Gruber, J.Vaclavik, Comput.Phys.Reports **4** (1986) 95

[10] D. Gambier, A. Samain, Nucl. Fusion **25** (1985) 283

[11] G.A.Collins, F.Hofmann, B.Joye, Phys. Fluids **29** (1986) 2260

[12] K.Appert, T.Hellsten, J.Vaclavik, L.Villard, Comput. Phys. Commun. **40** (1986) 73

[13] J. Vaclavik, K. Appert, Nucl. Fusion **31** (1991) 1945

[14] A. Jaun, A. Fasoli, W.W. Heidbrink, Phys. Rev. Lett., submitted

[15] A. Fasoli, J. Lister, J.-M. Moret, S. Sharapov, D. Borba, G. Bosia, D. Campbell, J. Dobbing, C. Gormezano, J. Jacquinot, P. Lavanchy, Ph. Marnillod, A. Santagiustina, Phys. Rev. Lett. **75** (1995) 645

[16] A. Jaun, K. Appert, J. Vaclavik, L. Villard, Comput. Phys. Commun. **92** (1995) 153

[17] *Fast Wave Heating and Current Drive in ITER*, Eur. Coord. Comm. on Fast Wave Current Drive and Heating (CCFW), edited by V. Bhatnagar, J. Jacquinot, NET Report EUR-FU/XII/163/94 (1994)

[18] L.-G. Eriksson, T. Hellsten, Nucl. Fusion **29** (1989) 875