

## The effects of kinetic power flow on high harmonic fast wave heating

R. A. Cairns, V. Fuchs, and C. N. Lashmore-Davies

Citation: *AIP Conf. Proc.* **403**, 313 (1997); doi: 10.1063/1.53427

View online: <http://dx.doi.org/10.1063/1.53427>

View Table of Contents: <http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=403&Issue=1>

Published by the [American Institute of Physics](#).

---

### Related Articles

The dependence of extracted current on discharge gas pressure in neutral beam ion sources on HL-2A tokamak  
*Rev. Sci. Instrum.* **83**, 023302 (2012)

First neutral beam injection experiments on KSTAR tokamak  
*Rev. Sci. Instrum.* **83**, 02B102 (2012)

Beta dependence of electron heating in decaying whistler turbulence: Particle-in-cell simulations  
*Phys. Plasmas* **19**, 012312 (2012)

Energy budgets in collisionless magnetic reconnection: Ion heating and bulk acceleration  
*Phys. Plasmas* **18**, 122901 (2011)

Generation of high-current electron beam in a wide-aperture open discharge  
*Phys. Plasmas* **18**, 103112 (2011)

---

### Additional information on AIP Conf. Proc.

Journal Homepage: <http://proceedings.aip.org/>

Journal Information: [http://proceedings.aip.org/about/about\\_the\\_proceedings](http://proceedings.aip.org/about/about_the_proceedings)

Top downloads: [http://proceedings.aip.org/dbt/most\\_downloaded.jsp?KEY=APCPCS](http://proceedings.aip.org/dbt/most_downloaded.jsp?KEY=APCPCS)

Information for Authors: [http://proceedings.aip.org/authors/information\\_for\\_authors](http://proceedings.aip.org/authors/information_for_authors)

### ADVERTISEMENT



AIP Advances

*Submit Now*

Explore AIP's new  
open-access journal

- Article-level metrics now available
- Join the conversation! Rate & comment on articles

# The Effects of Kinetic Power Flow on High Harmonic Fast Wave Heating

R. A. Cairns\* V.Fuchs<sup>‡</sup> and C.N.Lashmore-Davies<sup>#</sup>

*\*University of St Andrews, St Andrews, Fife, KY16 9SS, UK.*

*‡Centre Canadien de Fusion Magnétique, Varennes, Québec, J3X 1S1, Canada.*

*#UKAEA Fusion, Culham, Abingdon, Oxon. OX143DB. (UKAEA/Euratom Fusion Association)*

**Abstract.** We apply a fast wave approximation to the propagation of the fast wave across the magnetic field. This approximation involves replacing the hot plasma conductivity tensor by an approximation which reduces the problem to a second order differential equation. Such a procedure is particularly useful in the high harmonic regime, where many terms with the full Bessel function dependence must be retained in the dielectric tensor. However for conditions anticipated in low aspect ratio tokamaks, there are regions of the plasma in which a substantial fraction of the power is carried by the particle kinetic flux, and this must be accounted for if correct results are to be obtained.

## INTRODUCTION

In order to heat the plasma in a small aspect ratio tokamak such as NSTX [1] or MAST [2], Ono [3] has proposed a scheme using the fast wave at a high harmonic of the ion cyclotron frequency. He shows that in the high  $\beta$  plasma typical of small aspect ratio tokamaks, effective heating of both electrons, by a combination of Landau damping and TTMP, and ions, by cyclotron damping, can take place.

In this paper we derive an approximate second order equation to describe the propagation of the fast wave across the machine. In order to obtain the appropriate form of the equation and show that it gives physically reasonable results we use a plane slab geometry. The fast wave approximation, in its simplest form, replaces the hot plasma conductivity, an operator, with a local value calculated using the cold plasma perpendicular wavenumber. It yields good results for minority and second harmonic heating under standard tokamak conditions [4,5]. In these problems it makes little difference whether the cold plasma value of  $k_{\perp}$  or the exact local value, coming from the full dispersion relation, is used. However, for the high  $\beta$  plasma we have found that it does make a significant difference. In the next section we show that this difference arises because there is a substantial contribution to energy transport from the particle kinetic flux. We then discuss the appropriate form of the fast wave equation to take account of this kinetic energy flux and present some preliminary results.

## THE WAVE EQUATION

The objective of the fast wave approximation is to reduce the problem of wave

propagation across the field which, for large Larmor radius, involves very complicated integro-differential equations [6,7,8], to a second order differential equation which gives a good approximation to the overall absorption and reflection of the wave but loses the distinction between local absorption and mode conversion.

The most obvious equation to try is of the form

$$\frac{d^2 E}{dx^2} + V(x, k_{\perp}^2) E = 0 \quad (1)$$

where  $V(x, k_{\perp}^2)$  is simply evaluated locally so as to give the correct local value of  $k_{\perp}^2$ . We regard  $V(x, k_{\perp}^2)$  as a function of  $k_{\perp}^2$  since we wish to include incident and reflected waves in a symmetrical way. For a high  $\beta$  plasma we find that quite different results are obtained depending on whether we use the exact local value of  $k_{\perp}^2$  or the cold plasma value. If the latter were acceptable, it would, of course allow us to avoid the calculation involved in finding the exact root.

The reason for this difference may be seen if we take the exact root to be given by  $k_{\perp} = k_1 + ik_2$ . Assuming  $k_2 \ll k_1$  we can write

$$V(x, k_{\perp}^2) \approx V(x, k_1^2) + ik_2 \frac{\partial V(x, k_1^2)}{\partial k_1} \quad (2)$$

and derive the conservation relation

$$\frac{d}{dx} (\text{Im}(E^* \frac{dE}{dx})) + \text{Im}(V)|E|^2 + k_2 \text{Re}(\frac{\partial V}{\partial k_1})|E|^2 = 0 \quad (3)$$

where we identify the three terms in this equation as the divergence of the Poynting flux, the dissipation rate and the divergence of the kinetic flux. However, the divergence of the kinetic flux only contains the rate of change of the wave intensity due to damping, not the effects of plasma inhomogeneity. We now outline a heuristic attempt to derive an equation which will include the extra contributions to the kinetic flux and give the correct overall energy balance in this wave propagation problem.

When a small Larmor radius expansion is valid, we normally expand the conductivity as a series in  $k_{\perp}$  and take the powers of  $k_{\perp}$  to correspond to derivatives. In our case we cannot justify such an expansion. What we can do is argue that the dominant Fourier components present locally in the wave correspond to the incoming and reflected waves in the local approximation. We thus expand  $V(x, k_{\perp}^2)$  by writing

$$V(x, k_{\perp}^2) \approx V(x, k_0^2) + (k_{\perp}^2 - k_0^2) \frac{\partial V(x, k_0^2)}{\partial k_0^2} \quad (4)$$

where  $k_0^2$  is the local solution of the dispersion relation. This satisfies  $k_0^2(x) = V(x, k_0^2)$  but in taking the derivative we must, of course, take  $V$  to be

the expression derived from the dielectric tensor, with Bessel functions summed over whatever harmonics are important. We now identify the term  $k_{\perp}^2$  with a second derivative acting on the field. Thus the procedure is similar to the standard small Larmor radius expansion, only now we are not saying that the change in the field is small over a Larmor radius, but rather that it is close to the rate of change given by the local wavenumber. By treating forward and backward propagating waves on the same footing, we can, unlike the standard WKB method, include reflected waves. We thus obtain the equation

$$\frac{d^2 E}{dx^2} - \frac{d}{dx} \left( \frac{\partial V}{\partial k_0^2} \frac{dE}{dx} \right) - k_0^2 \frac{\partial V}{\partial k_0^2} E + V(k_0^2) E = 0 \quad (5)$$

In placing the derivatives in the form given in the second term we are simply working by analogy from the small Larmor radius case. In the WKB limit equation (5) can be shown to give the expected conservation law .

## RESULTS AND CONCLUSION

The diagrams on the following page show some results for a plasma with  $T_e=1\text{keV}$ ,  $T_i=0.3\text{keV}$ , plotting various quantities across the mid-plane of a tokamak of major radius 64cm. They show local values, with the electric field taken to have the same magnitude everywhere. In practice, the decay of the field across the plasma would have to be included, but the present plots give a better idea of the different contributions to energy transport. The first shows contributions to  $\mathbf{J}\cdot\mathbf{E}$  from TTMP (2), electron Landau damping (3), cross terms (x) and from ions. Note that the ion contribution is negative. The following two diagrams show the dissipation coming from the individual terms, as in the first diagram, and for each species in total, and the last one shows the kinetic fluxes. Note that the negative  $\mathbf{J}\cdot\mathbf{E}$  from the ions arises because of a change in the kinetic flux, and that ion dissipation is positive. The fact that the local transfer out of the ions into kinetic flux can outweigh the energy going into them from dissipation shows the importance of this flux. Further work will investigate in more detail the formulation of energy-conserving fast wave approximations and the contribution of kinetic fluxes to energy flow in the problem of high harmonic fast wave heating.

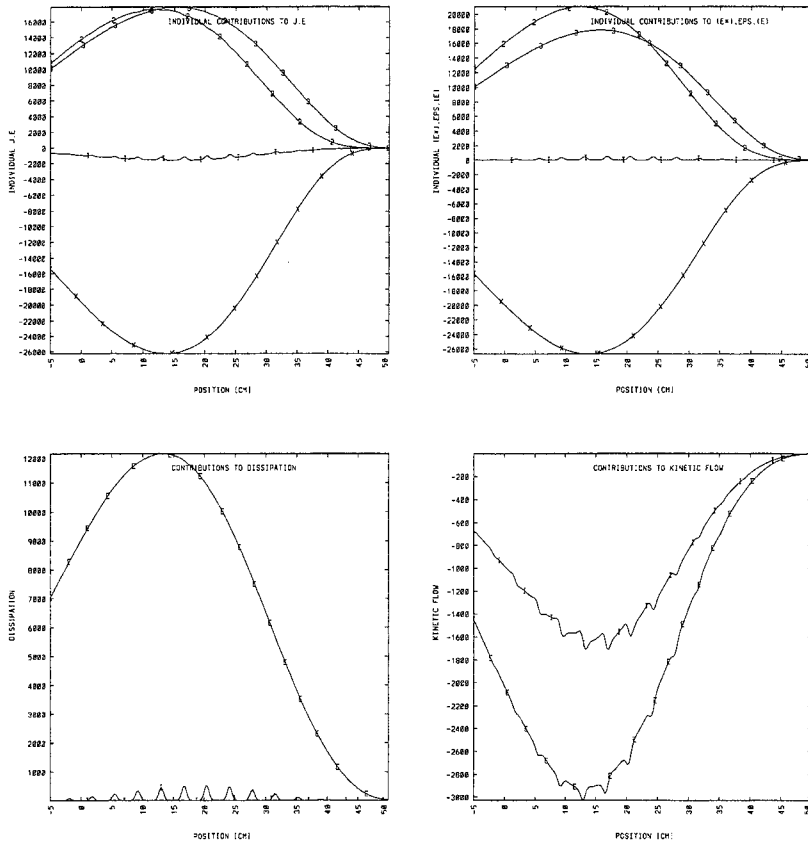
## ACKNOWLEDGEMENTS

This work was jointly funded by the UK Department of Trade and Industry and Euratom. Support was also provided by the UK Engineering and Physical Sciences Research Council, Grant GR/K 58937. The Centre canadien de fusion magnétique is a joint venture of Hydro-Québec, Atomic Energy of Canada Ltd and the Institut national de la recherche scientifique, in which MPB Technologies and Canatom, Inc. also participate.

## REFERENCES

- [1] Spitzer J et al, *Fusion Technology* **30**, 1337 (1996)

- [2] Robinson D C et al, *Fusion Technology* **30**, 1360 (1996)  
 [3] Ono M, *Phys. Plasmas* **2**, 4075 (1995)  
 [4] Kay A, Cairns RA and Lashmore-Davies CN, *Plasma Phys. Contr. Fus.* **30**, 471 (1988)  
 [5] Lashmore-Davies, CN et al, *Phys. Fluids* **31**, 1614 (1988)  
 [6] Sauter O and Vaclavik J, *Nuclear Fusion* **32**, 1455 (1992)  
 [7] Brambilla M, *Plasma Phys. Contr. Fus.* **33**, 1029 (1991)  
 [8] Cairns RA et al, *Phys. Plasmas* **2**, 3702 (1995)



**FIGURE 1.** This figure shows how various quantities, as described in the text, vary across the mid plane of a torus with the dimensions of NSTX. The horizontal axis goes from -5cm to 50 cm, measured from the major axis at a radius of 64cm. The vertical axes may be regarded as being in arbitrary units