GA–A25791

TIME-DEPENDENT MODELING OF NONLINEAR PLASMA RESPONSE TO FAST WAVES WITH MULTIPLE DAMPING MECHANISMS

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JUNE 2007

GENERAL ATOMICS

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This is a preprint of a paper to be presented at the 17th Topical Conf. on Radio Frequency Power in Plasmas, Clearwater, Florida, May 7-9, 2007, and to be published in the *Proceedings.*

Work supported by
the U.S. Department of Energy
under DE-FC02-04ER54698

GENERAL ATOMICS PROJECT 30200
JUNE 2007

Time-Dependent Modeling of Nonlinear Plasma Response to Fast Waves With Multiple Damping Mechanisms

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Abstract. Recent DIII-D experiments on the absorption of fast waves (FWs) by moderate to high ion cyclotron harmonic damping [R.I. Pinsker, *et al.*, *Nucl. Fusion* **46**, S416-S424 (2006)] have motivated a substantial modeling effort within the RF SciDAC community, but as of yet, the time dependence of the plasma response has not been modeled. In this work, a simple 0-D time dependent absorption and transport model is used to predict the plasma response to a step in FW power when multiple FW absorption mechanisms are present. When the plasma has a nonlinear response to at least one of the damping mechanisms, both the partition between the various absorption channels in the steady-state solution and the time required to reach the final state depend strongly on the initial conditions.

Keywords: radio frequency heating, fast waves, damping mechanisms
PACS: 52.50.Qt, 52.25.Os, 52.35.Mw

COMPETITION BETWEEN MULTIPLE FAST WAVE ABSORPTION MECHANISMS

Fast waves (FWs) in the ion cyclotron range of frequencies can deposit energy in the core of a tokamak plasma by several different damping mechanisms, including direct electron damping and by ion cyclotron harmonic damping on thermal and non-thermal ion species. Furthermore, FW power can be absorbed in the edge plasma by dissipation in sheaths, parametric decay instability, collisional damping and various other mechanisms. In experiments, all of these absorption mechanisms are present simultaneously. In the modeling of these experiments, most of the studies to date have allowed for only a single damping mechanism at a time. In the work by Jaeger, et al. [1], absorption by Maxwellian electrons by direct electron absorption, ion cyclotron absorption on Maxwellian hydrogen minority ions, and ion cyclotron absorption on a non-thermal deuterium population (initially from neutral beam injection) are simultaneously accounted for, but the possibility of two or more nonthermal distribution functions is deferred to future work. Furthermore, in the iteration scheme used in that work, in which a field solver (AORSA) is coupled to a Fokker-Planck code (CQL3D), the temporal evolution of the nonthermal deuterium distribution function is not calculated. Instead, the iteration continues until the solution does not change with further iteration, which is taken to be the actual steady-state condition.

In a recent discussion within the RF SciDAC group, it was pointed out that in the case of more than one absorption mechanism, the steady-state solution could depend sensitively on the initial condition, and hence the solution found by iteration would not be unique. To evaluate the possible importance of such an effect, we study the time development of rf absorption in a case with at least two different absorption mechanisms. We assume that the plasma response to FW power absorption by at least one of the mechanisms is nonlinear in FW field amplitude. Realistic examples include:

1) direct electron absorption, in the (usual) regime in which single-pass absorption increases rapidly with electron temperature, competing with a fixed edge loss per bounce (such as might arise from sheath dissipation),

2) absorption on a superthermal deuterium population from deuterium neutral beam injection and on a hydrogen minority at half the harmonic number (both mechanisms have the important nonlinearity – the more power that is absorbed on a given species, the stronger the tail in that species becomes and the stronger the single-pass absorption), and

3) combinations of the above mechanisms.

After obtaining a steady-state condition in the absence of the FW power, the FW power is turned on step-wise at a power level sufficiently high that the nonlinearity is relevant and the evolution of the power division among the different absorption channels is analyzed. It is apparent that the ultimate (steady state) division of power among the competing absorption mechanisms will depend on the initial conditions. In the first example (above), the higher the initial electron temperature, the stronger the single-pass absorption on electrons, so the higher the ratio of core absorption to edge absorption and the larger the ultimate fraction of power absorbed in the core. In the second example, if the hydrogen minority starts with a high-energy tail (for example, if the neutral beam fueling gas were a mixture of H and D), stronger absorption at half the harmonic could overcome the smaller hydrogen density compared with the density of the energetic deuterium and the hydrogen tail would grow, absorbing an increasing fraction of the rf power. To the extent that iteration between a field solver like TORIC or AORSA and a quasilinear package like CQL3D or ORBIT-RF is similar to following the time development of the absorption, the converged solution will depend on the initial condition assumed (and is not unique); the final division of power among the competing absorption mechanisms will depend on the initial conditions.

DIRECT ELECTRON ABSORPTION AND EDGE LOSSES

To make these qualitative considerations more concrete, case (1) above is modeled: competition between direct electron damping in the core and an unspecified fixed edge loss per bounce. A simple slab model of the dynamics of the absorption, including ohmic heating and a finite energy confinement time τ_e is given by

$$\frac{dT_e}{dt} + \frac{T_e}{\tau_e} = \frac{P_e}{n_e V} = \frac{1}{n_e V}\left\{ C T_e^{-3/2} + P_{rf} \frac{\eta_{core}}{\eta_{core} + \eta_{edge}} \right\} \qquad (1),$$

in which $\eta_{core} \approx \mathrm{Im}(k_\perp)a$, the minor radius is a, (I assume that the single-pass absorption η_{core} and the loss per bounce from the plasma edge η_{edge} are both small

compared to unity), $\mathrm{Im}(k_\perp) \approx \mathrm{Re}(k_\perp)\sqrt{\pi/2}\,\beta_e\zeta_e \exp(-\zeta_e^2)$, with $\zeta_e = V_{ph}/V_{the}$, $V_{the}^2 = 2T_e/m_e$, $V_{ph} = \omega/k_{||} = c/n_{||}$, and $\mathrm{Re}(k_\perp) \approx \omega/V_A$ with V_A the Alfvén speed. The constant C in Eq. (1) is determined by the ohmic heating power before the rf turn-on at t=0. It is assumed that power deposited in the edge is not confined so that P_e is the electron heating power (ohmic plus rf) in the core, and that the core density is constant. (A more sophisticated model could assume a density rise proportional to the power deposited in the edge plasma.) Parameters typical of 60 MHz DIII-D FW direct electron heating experiments [2] are taken: deuterium plasma, toroidal field of 1 T, electron density of 2×10^{19} m^{-3}, FW power of 1 MW, $n_{||} = 5.4$ at the plasma center, volume within $a/2$ of ~4.3 m^3. For these parameters, the single pass core absorption on electrons η_{core} varies from 0.04% for $T_e = 1.1$ keV to 1.9% for $T_e = 2.0$ keV. Hence, one expects nearly none of the rf power to be absorbed in the core for an initial temperature of 1.1 keV for edge loss levels on the order of 1% per bounce or more. (Loss levels of 4% per pass were invoked to explain the observed central FW current drive efficiency in low-density L-mode discharges in Ref. [3].)

The results of this simple simulation, shown in Fig. 1, demonstrate that both the final partitioning of power between the two absorption mechanisms and the time required to reach a steady state are sensitive to the initial condition. In the marginal case, a steady-state condition is not yet attained after five electron energy confinement times. If the edge loss is assumed to be large enough, no substantial core absorption is predicted on any reasonable timescale for initial absorption levels in the range considered here. The results are summarized in Fig. 2, which shows the increment in central temperature after five energy confinement times as a function of the initial core temperature. The slight decline in ΔT_e with increased single-pass absorption in the case without edge loss is due to the drop in ohmic power with electron temperature.

DISCUSSION AND CONCLUSIONS

The important features of the simulation results – that the final division of power between the competing absorption mechanisms can be strongly sensitive to the initial condition, and that the evolution of the plasma response to a FW power step also

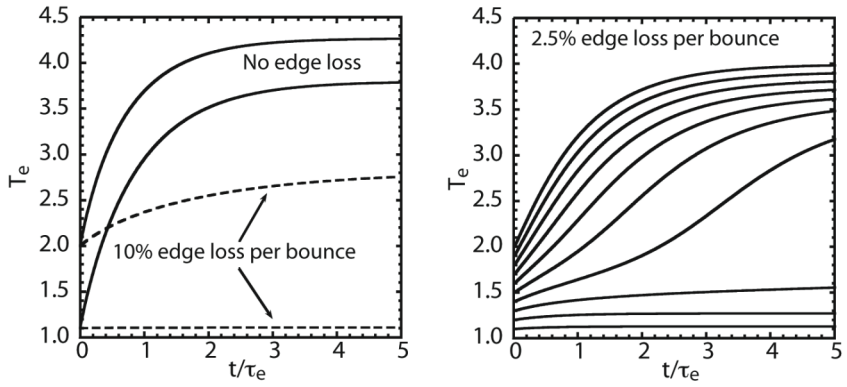

FIGURE 1. Time histories of core electron temperature for three different levels of assumed edge loss per bounce. In the left panel, initial temperatures of 1.1 and 2.0 keV are assumed, while in the right panel, ten initial temperatures between 1.1 and 2.0 keV are shown. Parameters are given in the text.

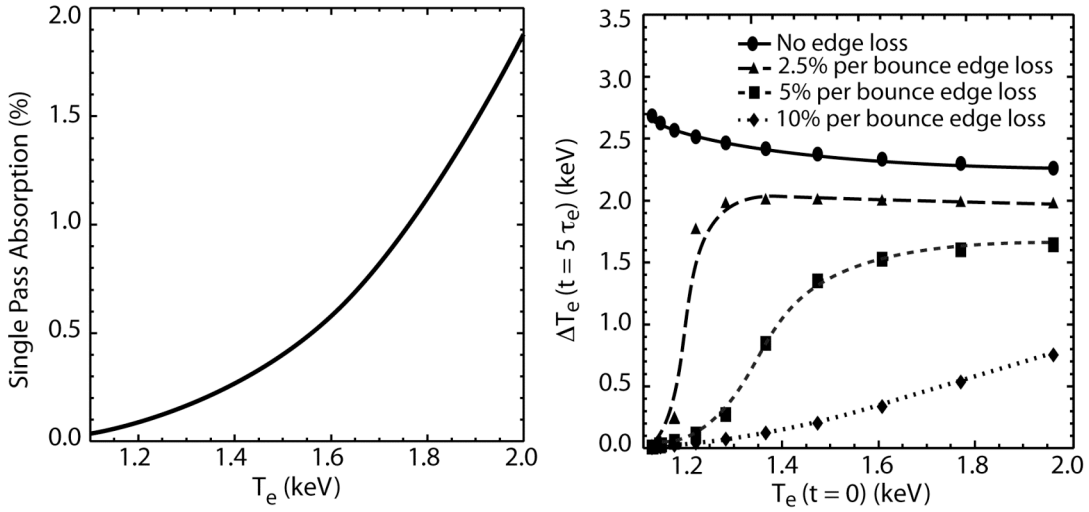

FIGURE 2. Single-pass absorption (left) and the increase in core electron temperature after five energy confinement times (right) plotted as functions of the initial core temperature, the latter for four values of edge loss.

depends on the initial condition – are not dependent on details of a particular absorption mechanism. These effects are generic when the plasma response to rf power absorption via at least one of the damping mechanisms is significantly nonlinear. The response to FW power absorption by ion cyclotron harmonic absorption on an energetic tail is more strongly nonlinear than to direct electron damping examined here, so that one expects in the case of competition between hydrogen and deuterium cyclotron damping (at twice the harmonic number) the result will depend strongly on the initial damping rates on the two ion species. If the hydrogen is initially thermal and sufficiently dilute (as it is in most DIII-D cases with deuterium beam injection), a hydrogen tail will not develop if the damping on the deuterium beam is non-negligible.

A simulation of that competition is more involved, due to the non-Maxwellian distribution functions and lack of simple analytic forms for the damping. The next step should be to study the evolution of the damping in this case using a time dependent Fokker-Planck solver that includes multiple ion species. The actual experiment is even more complicated, in that direct electron damping, both hydrogen and deuterium ion cyclotron damping, and edge losses are all simultaneously present.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under DE-FC02-04ER54698. The author would like to thank M. Porkolab and the members of the RF SciDAC team for stimulating his interest in this topic and for many useful discussions.

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