PARTICLE SIMULATION OF INTENSE ELECTRON CYCLOTRON HEATING AND BEAT-WAVE CURRENT DRIVE

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High-power free-electron lasers (FEL) make new methods possible for heating plasmas and driving current in toroidal plasmas with electromagnetic waves. We have undertaken particle simulation studies with one and two dimensional, relativistic particle simulation codes EMONE [1] and ZOHAR [2] of intense pulsed electron cyclotron heating and beat-wave current drive [3]. The particle simulation methods here are conventional: the algorithms are time-centered, second-order-accurate, explicit, leap-frog difference schemes. The use of conventional methods restricts the range of space and time scales to be relatively compact in the problems addressed. Nevertheless, experimentally relevant simulations have been performed.

An intense FEL [4] at the Lawrence Livermore National Laboratory ETA-II facility will be used to heat the Alcator C tokamak with microwaves (MTX experiment) [5]. Because of the intense electric fields anticipated in MTX, $E \sim 500$ kV/cm, resonant electrons can rapidly heat and relativistically detune themselves from cyclotron resonance. A trapping oscillation then ensues, and the electron energy can then decrease. Superadiabatic motion is rendered stochastic by a number of possible mechanisms, e.g., the finite spatial domain of the microwave pulse as seen by the electrons transitting around the torus. Absorption is altered from its linear value when the trapping period is shorter than the transit time through the pulse [6]. The opacity is reduced by the trapping from its linear value and is further reduced by nonlinear effects when the nonlinear trapping dominates the thermal effects in determining the resonance width. A detailed analysis of the nonlinear opacity is presented in Ref. 6. Crucial to the success of the MTX experiment is whether the opacity realized will ensure that most of the microwave power is absorbed in the heart of the tokamak.

Because the wave frequency of the FEL is well matched to the electron cyclotron frequency and $\omega_{pe}^2 \lesssim \omega_{ce}^2$, the problem of short-pulsed highly nonlinear electron cyclotron heating in MTX is well suited to conventional particle simulation. We have used the 2 1/2-dimensional relativistic electromagnetic particle simulation code ZOHAR written by Langdon and Lasinski [2]. The domain is periodic in the direction of the background magnetic field which is a function of the orthogonal spatial coordinate. Because the simulation is completely self-consistent, the model naturally includes wave attenuation effects and the nonlinear back-reaction of the plasma heating on the wave propagation. The microwaves are normally incident with respect to the applied magnetic field and are introduced through a finite aperture. Absorbing boundary conditions are used in the direction normal to the magnetic field at both boundaries. With 96000 particles of each species and a 100 × 128 mesh, a series of simulations with 3000 time steps ($\omega_{ce} dt = 0.2$) were performed. Results for the opacity $\tau = -\ln$ (power transmitted/power incident) as a function of the parameter $p_1 = [N_\parallel (E_\parallel / B_0)\ (m_e c^2/T_e)]^{2/3}$ for ordinary mode heating are shown in Fig. 1. Here $N_\parallel = k_\parallel c/\omega$ is the parallel index of refraction, and $E_\parallel$ is the microwave electric field. The degradation of the absorption with increasing wave amplitude is clear, and the agreement with the scaling arguments of Ref. 6 is quite good. The reduction in opacity with mobile ions for $p_1 > 1$ is attributed to the effect of nonlinear self-focussing observed in the simulations, which further increased the local electric field intensity (and the effective value of p_1) and decreased the absorption in consequence. MTX will operate in a regime where $p_1 > 1$ but with a much wider absorption zone than is possible to model in the simulations, so that the opacity will exceed 2.5 [6]; and self-focussing is not expected to occur.

An important associated issue in assessing the success of intense ECH in MTX is the possibility of parametric instabilities [5,7]. ZOHAR has achieved considerable success in simulating parametric instabilities in the context of laser fusion [8]. With the addition of the background applied magnetic field, the analogous study of parametric instabilities accompanying intense ECH can be undertaken. The presence of the magnetic field allows a richer variety of phenomena. Analysis of the proposed operation of MTX suggests that Brillouin backscattering by electrostatic ion cyclotron waves will exceed linear thresholds [7]. We have begun simulation studies of Brillouin scattering in ZOHAR in an effort to determine its nonlinear saturation and the actual level of reflectance to be expected in MTX. Because of the physics requirements, these simulations are necessarily two dimensional and must span many space and time scales. The problem is amenable neither to adaptive gridding nor implicit methods; and hence, it is quite a stiff problem.

A detailed simulation study has been made with EMONE to examine the possibility of beat-wave current drive in MTX and a reactor-relevant tokamak experiment [9]. Here the beating of two electromagnetic waves resonantly excites a low-frequency beat wave that accelerates and heat electrons, which in turn leads to a current. The absolute current-drive efficiency depends nonlinearly on the two pump-wave intensities and is constrained by the Manley-Rowe relations [3]. Accessibility at high plasma densities is not a difficulty, but a degree of frequency tunability in the wave sources is required. One and a half dimensional simulations in EMONE with periodic boundary conditions model the beat-wave coupling as an initial-value problem. The simulation model naturally incorporates the essential nonlinearities: the nonlinear ponderomotive coupling of the electromagnetic waves to the beat wave, the nonlinear interaction of the finite-amplitude beat wave with the plasma and its possible coupling to ion modes. The particle simulations indicate that there is good coupling to an electron velocity tail for a Langmuir beat wave (assumed to be propagating parallel to the tokamak magnetic field) with a phase velocity 3 or $4(T_e/m_e)^{1/2}$, so that all of the high-frequency electromagnetic wave source is absorbed and the beat wave damps completely on the electrons. Momentum and energy transfer to the plasma is observed to be consistent with the Manley-Rowe constraints. Parasitic processes involving the ions were minimized in this range of phase velocities. A typical simulation is shown in Fig. 2 for the case of counter-propagating electromagnetic pump waves.

A realistic scenario for a beat-wave current-drive experiment in the Livermore MTX experiment has been calculated using EMONE and a toroidal ray tracing code [9]. We have also analyzed the current-drive efficiency expected for beat-wave current drive when collisions are included. This has motivated the use of a novel code diagnostic due to R. Cohen, in which a Green's function solution of the Fokker-Planck problem is used to calculate the average integrated current carried by the perturbed electron distribution as it collisionally relaxes [10]. This quantity peaks as a function of the beat-wave phase velocity in the range 3.5 to 4.5 $(T_e/m_e)^{1/2}$ for both parallel and counter-propagating electromagnetic pump waves. These simulations should be extended to incorporate a background applied magnetic field, plasma inhomogeneity [1], and a finite illumination zone so as to address the space-time evolution and finite-resonance-zone effects. However, this introduces an additional space scale into what is already a costly simulation (runs are of order one-half to one hour on a CRAY 1).

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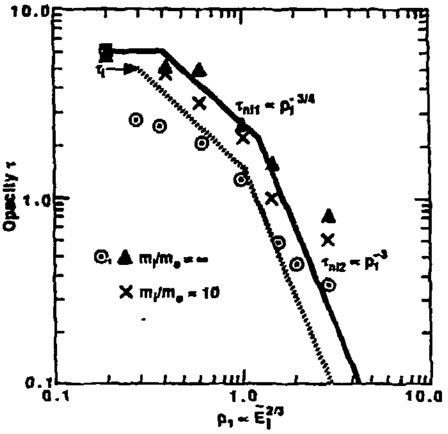
FIGURE 1. The nonlinear opacity $\tau = -\ln$(power transmitted/power incident) as a function of ρ_i proportional to $E_H^{2/3}$. Simulation results with immobile ions ($m_i/m_e = \infty$) and mobile ions ($m_i/m_e = 10$) are shown. The dashed and solid lines indicate a fit to the analytical scaling theory of Ref. 6. The data at the right, i.e., increased absorption at the same value of ρ_i, was obtained with an increased slab width and resonance zone.



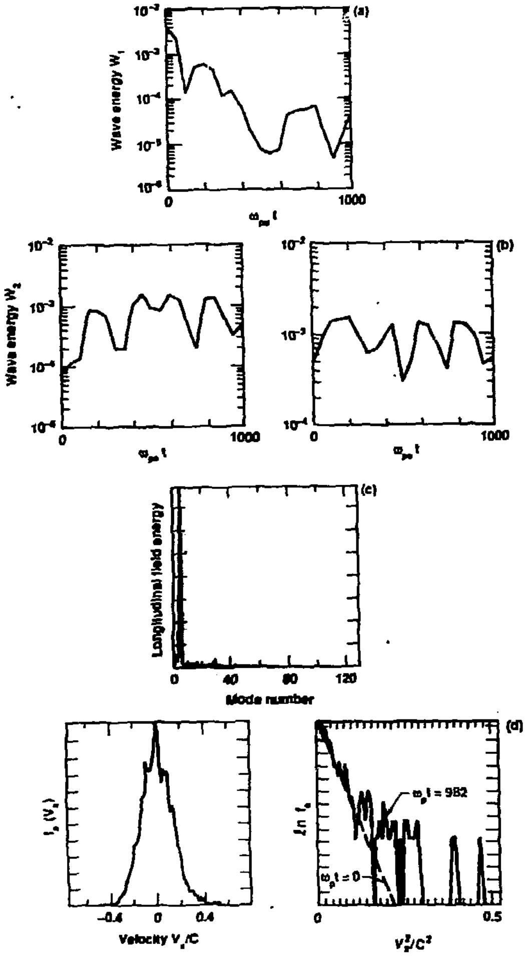


FIGURE 2. Particle simulation results for opposed propagation of transver pump waves. (a) The higher frequency pump-wave energy density vs. time showing pump depletion. (b) The lower frequency pump-wave energy density components vs. time. (c) The longitudinal field energy spectrum vs. wavenumber showing the beat-wave peak. (d) The electron velocity distribution vs. velocity parallel to the beat-wave propagation at the end of the simulation showing the formation of a tail. All of the beat-wave energy and momentum was absorbed by the electrons.