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5/9/80

DR. 1162

APRIL 1980

PPPL-1654

UC-20f

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COUPLING DUE TO THE PONDEROMOTIVE
FORCE

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This work was supported by the U.S. Department of Energy
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SUPPRESSION OF LOWER HYBRID WAVE COUPLING DUE TO THE
PONDEROMOTIVE FORCE

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ABSTRACT

The coupling efficiency from a slow-wave structure to lower hybrid waves is investigated experimentally. At moderate electric field strengths ($\frac{\omega_{pe}^2}{4\pi\omega^2 nT} |E_z|^2 \lesssim 1$) large edge density changes are observed. Wave trajectory modifications and departure from linear coupling are observed consistent with these changes and in good agreement with a simple nonlinear theory that includes the ponderomotive force.

To achieve thermonuclear temperatures in a tokamak plasma several auxiliary heating schemes have been proposed. One attractive scheme is to couple radio-frequency (rf) wave energy to lower hybrid waves which propagate to the center of the plasma and then deposit their energy into ions and electrons. At the power levels required for a reactor plasma the wave energy density can be comparable to the plasma pressure near the plasma surface; the ponderomotive force may then alter the density profile and degrade the coupling between antenna and plasma. (1-4)

We present an experimental study of the nonlinear coupling efficiency to lower hybrid waves from an external slow-wave structure. The results indicate that at high powers the coupling efficiency can be reduced by as much as 60% from the linear prediction. Results are found to be in agreement with a simple nonlinear theory⁽¹⁾ which takes into account the modification of the density profile near the antenna due to the ponderomotive force.

In addition to the change in coupling, a change in the resonance cone trajectory is observed in the region of the antenna.

Linear theory^(5,6) of lower hybrid wave coupling involves tunneling through an evanescent layer (where $\omega > \omega_{pe}$) in the low density region near the antenna. The important parameters governing coupling are the thickness of the evanescent layer and the steepness of the density gradient. Low power experiments have found good agreement with this theory.⁽⁷⁾

Nonlinear effects, in particular the ponderomotive force, are capable of decreasing the density gradient and increasing the width of the evanescent layer. (1,5)

From References 6 and 7 we know that at low density the reflection coefficient is a rapidly decreasing function of density. At larger values the coefficient flattens out and at high values it can turn up again. In our experiment we work at low densities ($\sim 1 \times 10^9/\text{cm}^3$) where a small change in density can cause a noticeable change in coupling. To investigate the coupling processes of lower hybrid waves, one should focus on the plasma edge near the critical layer where the wave frequency ω is comparable to the local electron plasma frequency ω_{pe} . Electromagnetic effects are important in this region so that the full set of Maxwell's equations should be used to analyze the coupling process. In a recent paper⁽¹⁾ the following one-dimensional equation for the self-consistent calculation of the density profile and the electric field for lower hybrid wave excitation was derived:

$$E_z'' + \frac{\omega_{pe0}^2(\xi)}{\omega^2} \exp(-|E_z|^2 - 1) E_z = 0. \quad (1)$$

Here E_z is the z ($||\vec{E}_0$) component of the wave electric field normalized to $(e^2/m_e \omega^2 T_e)^{1/2}$ and the primes denote differentiation with respect to $\xi = \frac{\omega}{c} \left| \left(\frac{ck_H}{\omega} \right)^2 - 1 \right|^{1/2} x$ the direction parallel to the density gradient. Numerical solution of this equation will be compared with experimental results below.

The experiment was conducted in the Princeton L-3 device, which is shown schematically in Figure 1. The steady-state plasma (2m long, 10 cm in diameter) is maintained by a multi-filament discharge ($n_{e0} \sim 7 \times 10^9 \text{ cm}^{-3}$, $B_0 \sim 1.6 \text{ KG}$, $P_0 = 3 \times 10^{-5} \text{ torr}$ argon, $T_e \sim .5\text{-}3\text{eV}$, $T_i < .1\text{eV}$). A multi-ring slow wave structure⁽⁸⁾ is used to launch the lower hybrid waves. A burst of rf ($\tau = 1\text{-}50\mu\text{s}$, $f = 90 \text{ MHz}$) is applied to two rings driven 180° out of phase. The rings are each 1.25 cm wide with an equal sized ceramic spacer between them. A double-tipped probe capable of scanning both axially and radially is used to measure both the electric field and plasma density profiles. A density constriction forms inside the antenna during the burst as the ponderomotive force pushes the electrons along the magnetic field out of the region of high electric field near the antenna. A potential is set up which pulls the ions along the field lines at the sound speed. The constriction does not seem to be due to the thermal eddies⁽¹³⁾ since it is axisymmetric and no significant heating is observed.

In Figure 2 we show the time evolution of the constriction depth and width. The depth saturates at a value consistent with $\frac{\delta n}{n_0} \sim \frac{\omega_{pe0}^2}{4\pi\omega^2 n T_e} |E_z|^2$.⁽¹⁾ The saturation time is consistent with the time for the plasma to move out of the central region of the antenna at the sound speed. The width continues to grow until pressure balance along the field line is achieved. In Figure 3 we show the relaxation of the perturbation. The following equations apply to the relaxation process.

$$\frac{\partial n}{\partial t} + \frac{2}{\partial x} (nv) = 0$$

$$\frac{\partial v}{\partial t} = v \frac{\partial v}{\partial x} = -v v - \frac{\partial \phi}{\partial x} - \frac{T_i}{T_e} \frac{1}{n} \frac{\partial n}{\partial x} \quad (2)$$

$$\frac{\partial^2 \phi}{\partial x^2} = e^{\phi} - n$$

Here n is normalized to n_0 the equilibrium density, v to C_s , x to λ_D , ϕ to $\frac{kT_e}{e}$ and v to $C_s/\lambda_D = \omega_{pi}$.

Without the collision term Equation 2 would lead to the generation of solitons⁽⁹⁾ which would propagate away from the initial perturbation. The presence of collisions however dumps the propagation leading to a relaxation as in Figure 3. The value of ν required to give this damping is $\sim 10^4 \text{ sec}^{-1}$ consistent with what would be expected in our plasma.⁽¹⁰⁾

The radial density profile is shown in Figure 4. The solid curves are the experimental profiles at an axial location midway between the rings. The points are from a numerical solution to Equation 1. The solution is found by integrating outwards from a point in the plasma, using the assumption of an inward propagating wave as a boundary condition. The rf pressure is seen to reduce the edge density and steepen the density gradient. Good agreement with theory is obtained.

Since the edge density has been depleted, a change in both resonance cone trajectory^(9,10) and coupling efficiency would be expected.

In Figure 5 we show the time evolution of the resonance cone trajectory. At 3 μ s into the burst the trajectory is almost unchanged from the linear case. At 10 μ s the trajectory has been strongly modified near the antenna and at 20 μ s the trajectory has bent to nearly perpendicular. In Figure 6 we plot the relative power in the propagating waves, as measured by a probe, versus the power at the antenna for two different edge densities. Accuracy has been improved by using the circuit of Figure 1 to make relative rather than absolute measurements of the probe signal. Attenuators on the rf input and probe output are ganged so that the product of their attenuation is constant, resulting in a constant probe signal if linear theory is valid. This also minimizes the effects of any nonlinearity of the crystal detector. The amount by which the received signal shrinks as the input power is raised is then a good measurement of the deviation from linearity of the coupling. The error bars in Figure 4 reflect the reproducibility of the measurements and the uncertainty in the actual power at the antenna, determined from the directional couplers immediately before the rings. Deviation from linear coupling is seen in the lowest edge density case at power above 0.5 watts, which corresponds to an electric field of ~5 V/cm or a value of

$$\frac{\omega_{pe}^2 |E_z|^2}{\omega^2 4\pi nT} \sim .23$$

at the plasma edge. At large powers the coupled power is reduced by as much as 60% from a linear extrapolation of low power couplings.

With a larger edge density the nonlinear effects arise at higher powers as predicted by theory, and the reduction in coupling at a given power is less.

If these effects persist in tokamak heating experiments, an upper limit may be placed on the power flux that can be coupled into a tokamak plasma. Several effects can mitigate these results.

Tokamak heating experiments operate in a higher edge density regime in which linear theory indicates a larger change in edge density would be required to effect coupling efficiency.

Secondly, ionization near the launching structure due to the rf could raise the edge density or at least maintain it. In a tokamak one could deliberately induce this by puffing gas in front of the waveguide if needed. In the nonaxisymmetric case of waveguide excitation plasma flows due to localized heating⁽¹³⁾ may be more important.

In conclusion, we have observed experimentally for the first time modification of the plasma density profile from high energy density lower hybrid waves. The coupling efficiency can be adversely effected when

$$\frac{\omega_p^2 E_z^2}{4\pi\omega^2 n T} \gtrsim 0.2 \quad .$$

The experimental results are in good agreement with a simple theory which takes into account the ponderomotive force.

We acknowledge useful discussions with R. W. Motley and M. Ono and technical assistance from J. Taylor and W. Kineyko. The work was done under U. S. Department of Energy Contract DE-AC02-76-CHO3073.

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(PPPL-803213)
Fig. 1. Schematic of experimental set up.

(PPPL-803156)
 Fig. 2. Density constriction evolution.
 a) depth of constriction vs time.
 b) width of constriction vs time.

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Fig. 3. Relation of density constriction.

(PPPL-803214)
 Fig. 4. Edge density profiles for various applied powers. Solid curves are experimental, points from numerical solution of Equation 1.

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 Fig. 5. Time evolution of resonance cone trajectory.

(PPPL-803215)
Fig. 6. Coupling efficiency vs applied power.