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Journal

Nuclear Fusion, 24(8)

ISSN

0029-5515

Authors

Olson, L
McWilliams, R
Glanz, J
et al.

Publication Date

1984-08-01

DOI

10.1088/0029-5515/24/8/010

LETTERS

COUPLING TO THE FAST WAVE VIA A PHASED WAVEGUIDE ARRAY

L. OLSON, R. McWILLIAMS*,
J. GLANZ, R.W. MOTLEY
(Princeton Plasma Physics Laboratory,
Princeton University, Princeton, New Jersey,
United States of America)

ABSTRACT. A dielectric-loaded waveguide array has been used to launch fast waves into a plasma in which $\omega_{pi} < \omega \ll \omega_{pe} \approx \omega_{ce}$. The wave propagates when accessibility and cut-off requirements are satisfied. Reflection coefficients as low as 1% have been measured. Use of the fast wave for steady-state current drive is suggested.

Slow electrostatic waves in the frequency range $\omega_{pi} < \omega < \omega_{pe}$ have been successfully employed to drive large currents in tokamak plasmas [1]. This mode, however, gives rise to a density limit at about one quarter of the density required to create a lower hybrid resonance in the centre of the plasma [2, 3]. It appears likely that the density limit would occur at higher density if the fast rather than the slow, mode were launched at the edge of the plasma [4]. Furthermore, the fast wave might be more suitable for current drive in hot, reactor-like plasmas, where the slow wave would be absorbed near the surface [5]. In this note we report the first efforts to develop a fast-wave waveguide coupler using a pair of waveguides loaded with Macor.

For both the slow and the fast wave there is an accessibility criterion which places an upper limit on the density to which the waves will propagate and a cut-off condition, which places a lower limit on that density [6]. Golant [7] has examined the cold-plasma dispersion relation equations for the slow and fast waves. Theilhaber and Bers [4] have discussed the coupling to the fast wave in more detail. The cut-off density is given approximately by

$$\omega_{pe}^2(\text{cut-off}) \approx \omega\, \omega_{ce}\, (n_z^2 + n_y^2 - 1)^{1/2}\, (n_z^2 - 1)^{1/2} \quad (1)$$

For $n_y \neq 0$, the cut-off density may rise or fall somewhat from Eq. (1), depending on whether $k_y dn/dx$ is greater or less than zero, respectively. The dispersion relation for the fast wave is approximately given by

$$n_x^2 \cong \left(\frac{\omega_{pe}^2}{\omega\omega_{ce}}\right)^2 \frac{1}{n_z^2 - 1} \quad (2)$$

In contrast to the slow lower hybrid wave, we observe that the fast wave does not propagate in the familiar resonance cones associated with the slow wave. Hence, it is less likely that ponderomotive effects [8, 9] and parametric decay [10] will be as significant as for the slow wave. On the other hand, electron Landau damping and transit time magnetic pumping can be important for the fast wave. The electron damping, coupled with the fact that the fast wave can penetrate to densities above the lower hybrid density makes the fast wave a good candidate for current drive.

The experiments were performed on the linear H-1 device [11] at Princeton utilizing an argon plasma approximately 3.4 cm in diameter and 200 cm long. The steady-state confining magnetic field, $\vec{B}_0 = B_0\,\hat{z}$, was typically 3 to 12 kG. The plasma was generated by a co-axial-gun RF discharge [12] pulsed ten times per second. Measurements were made in the afterglow plasma. Electron temperature was inferred from Langmuir probe traces and electron density from the phase shift of an 8.6 mm microwave interferometer. The fast waves were excited by application of 50 μs bursts at 2.45 GHz to a dielectric-loaded twin waveguide, as shown in Fig.1.

The fast wave launcher consists of two phased waveguides placed side-by-side and loaded with Macor ($\epsilon = 5.6$). This arrangement differs from the customary slow-wave grill in that the electric field of the guides is oriented perpendicular to rather than parallel to the confining magnetic field. Such an orientation is dictated by the polarization characteristics of the fast wave, in which the electric field parallel to the magnetic field is small. Each waveguide was 2.85 cm wide (along B) and 1.3 cm in height, so that the dominant mode (for 180° excitation) should be $n_z = 2.1$ and $n_y = 0$ with a spread in n_y of ± 4. In general, an antenna will couple to both the slow and fast modes but for this experiment we estimate that the cross coupling terms are small and little energy was available to the slow wave. The fast waves were

* Permanent address: Department of Physics, University of California, Irvine, California 92717, USA.

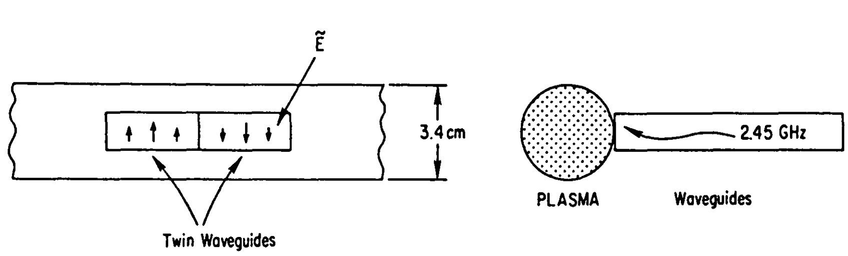

FIG.1. Diagram of linear plasma and twin waveguide designed to launch fast wave.

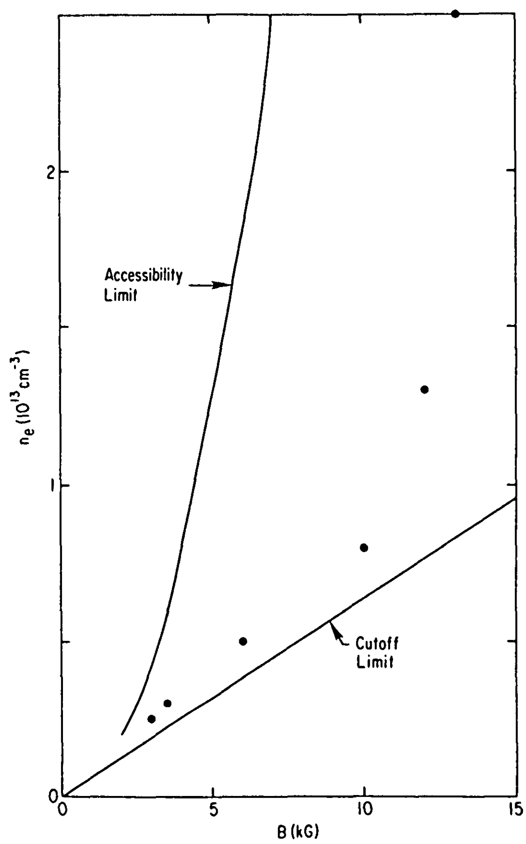

FIG.2. Density and magnetic field limits for propagation of 2.45 GHz fast wave in linear H-1 plasma. Dots indicate regions in which wave penetration beyond coupler mouth was detected with RF probe.

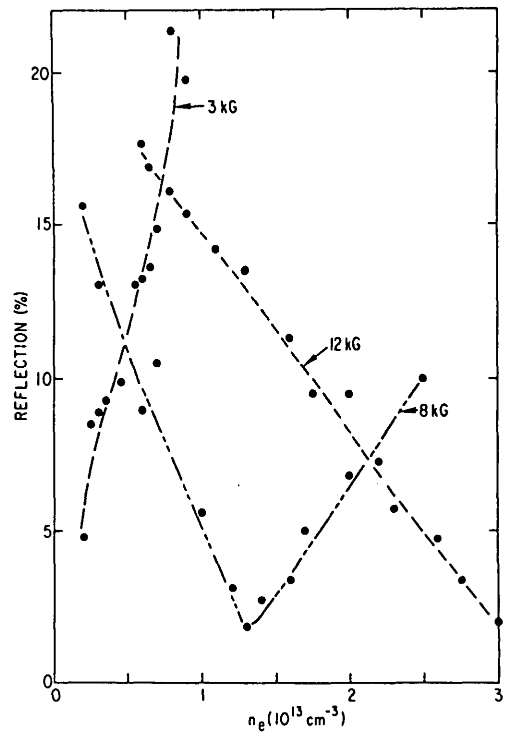

FIG.3. Reflection from twin guide as function of plasma density for three different magnetic fields.

detected by using a single tip tri-axial probe which could be moved in the axial or radial directions.

Figure 2 shows a graph of the region in density-magnetic field space where 2.45 GHz fast waves can propagate. The left- and right-hand solid lines represent the accessibility and cut-off limits as predicted by theory and the dots show where the fast wave was detected experimentally in the plasma. Outside of the propagating region, a surface wave could be detected at the edge of the plasma but no penetrating wave was found.

The coupling efficiency of the wave as a function of density, for three different values of B, is shown in Fig.3. Under the best coupling conditions, a reflection coefficient as low as 1% can be achieved. This compares well with the efficiencies which can be achieved with coupling to the lower hybrid wave. The coupling efficiency may be estimated by theory and compared with the experiment by calculating the impedance mismatch from the waveguide to the plasma. The plasma impedance is

$$Z \approx \frac{n_z^2 + n_y^2 - 1}{(n_z^2 - 1)^{1/2}} \frac{\omega\omega_{ce}}{\omega_{pe}^2} \qquad (3)$$

for $\omega_{pe}^2/\omega^2 \gg 1$ and $\omega_{pe}/\omega_c \approx 1$. Optimal matching to the plasma will occur if the plasma impedance matches the waveguide impedance. For our conditions ($n_z \approx n_y \approx 2$ and B = 8 kG) optimal coupling should occur if $n_e \approx 3 \times 10^{12}$ cm^{-3}. Integration over the broad wavenumber spectrum raises the optimal density close to 10^{13} cm^{-3}. From Fig.3, the optimal density at 8 kG is 1.5×10^{13} cm^{-3}.

The good coupling efficiency observed over a range of density near 1.5×10^{13} cm^{-3} contrasts with previous theoretical predictions [4] that the reflectivity would be 20% or greater. We speculate that the strong coupling results from the density profile near the mouth of the guide, which closely approximates a step function rather than a ramp, as assumed in the theory.

In conclusion, the fast wave near the lower hybrid frequency can be launched into plasmas from a loaded waveguide with high efficiency, provided the density and magnetic field are properly adjusted, and must be considered a candidate for RF current drive in tokamaks. The optimal strategy for efficient fast wave current drive would be to use a lower frequency (to minimize constraints on accessibility) and to reduce n_z below two (to interact with faster electrons). Such a strategy is suggested from Eq. (3), provided the coupler design minimizes n_y, so that the optimum plasma density near the mouth of the coupler remains moderate.

ACKNOWLEDGEMENT

This work was supported by the US Department of Energy Contract No. DE-AC02-76-CH0-3073.

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(Manuscript received 7 March 1984
Final manuscript received 28 May 1984)