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RF HEATING OF PLASMA**

BY

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**PLASMA PHYSICS
LABORATORY**

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Formation of Thermal Eddies During
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ABSTRACT

Moderate power (~ 1 kW) excitation of lower hybrid waves in a linear plasma column is found to increase the reflectivity of the phased waveguide exciter and to change the vertical position of the resonance cone. Probing of the plasma near the mouth of the waveguide reveals that the increased reflection results from an undulation in the plasma surface. We present evidence that this surface distortion is driven by thermal eddies associated with asymmetrical electron heating.

Radio frequency heating is considered a possible alternative to neutral beam injection for heating fusion plasmas to ignition temperatures.^{1,2} One method of applying the RF power is to launch waves at frequencies above the lower hybrid frequency into the surface plasma by means of phased waveguide arrays.^{3,4} In current reactor designs it is deemed necessary to supply $\sim 5 \text{ kW/cm}^2$ at the waveguide. This power must propagate to the plasma core without substantially altering the low density plasma near the mouth of the waveguide. It has been suggested that nonlinear processes, such as parametric wave decay^{5,6} or wave focussing by ponderomotive forces,^{7,8} might result in unacceptably high power losses in this critical surface layer. Although both of these processes have been observed experimentally^{9,10} their role in determining the nonlinear coupling effects observed in tokamak plasmas¹¹⁻¹³ has not been established. In fact, the physics of the interaction between the high amplitude plasma waves and the cool tenuous surface plasma is not well understood.

Previous studies of coupling to electrostatic plasma waves via phased waveguide arrays¹⁴ have demonstrated that the wave reflection can be satisfactorily explained by the linear theory of Brambilla.⁴ In this paper we show that moderate power ($\sim 1 \text{ kW}$ or 40 W/cm^2) wave excitation leads within $\sim 20 \mu\text{s}$ to the formation of a thermally-induced undulation in the surface plasma that increases the reflectivity of the twin waveguide exciter and shifts the region of maximum power

transmission from the center towards one end of the guide.

The experimental arrangement consisted of a 6 x 4 cm twin, teflon-loaded, phased waveguide exciting electrostatic waves in 2m long, 10 cm diam. linear plasma. The argon plasma of density $1-2 \times 10^{12} \text{ cm}^{-3}$ is formed by an RF ring discharge in a strong magnetic field ($< 16 \text{ kG}$).¹⁵ Shortly after the end of the discharge a 5-100 μs burst of RF power (0.2-8 kW) at 2.45 GHz was launched from the waveguide into the cold afterglow plasma ($1 < T_e < 1.5 \text{ eV}$).

The measured reflection coefficient was strongly affected by the phasing of the two waveguide elements, as found in low power studies.¹⁴ When adjacent waveguide elements were excited in phase, the reflectivity was ~50%; if the elements were excited out of phase, the reflection dropped to ~4%, because short wavelength penetrating electrostatic plasma waves are then efficiently generated. However, if the power level in the waveguide was raised above ~ 300 watts (at 180° phasing) the reflection coefficient increased from ~4% to ~12% in ~40 μs .

Since the reflection is affected by the plasma within an evanescent layer of thickness $k_z^{-1} \sim 1 \text{ cm}$,⁴ we examined this region with two Langmuir probes, both of which moved on arcs, one primarily horizontal, the other vertical (Fig. 1). The vertical probe shows more clearly the nature of the perturbation that arises in 10-20 μsec (Fig. 2). One can see that there is an apparent vertical shift of the plasma column from

a position ~ 1 cm below the center line of the waveguide to ~ 1.5 cm above. The shift is in the $\hat{S} \times \hat{B}$ direction, where $\hat{S}$ is a unit vector in the direction of power flow in the waveguide. (The perturbation changes sign on reversal of the magnetic field). We therefore have a simple explanation of the increase in reflection, because in $\sim 20 \mu s$ the plasma is pushed about one evanescent distance (~ 1 cm) away from the waveguide below the center line. In fact, as the plasma layer in closest contact with the plasma drifts vertically, the region of strongest wave coupling and the cone structure of the RF fields, measured with an RF probe, also move vertically at the same rate.

We have investigated the origins of this undulating plasma surface distortion. From vertical and horizontal scans of the electron temperature and the space potential in the vicinity of the waveguide we conclude that the perturbation arises via cross field drifts in the electric fields established by asymmetrical heating of the plasma column, i.e., by thermally produced plasma eddies or convective cells. Horizontal scanning reveals clearly that the temperature is highest near the waveguide (~ 4 eV), dropping to ~ 3 eV in the interior, with $\partial T / \partial x \sim 0.5$ eV/cm. Vertically, as shown in Fig. 3, the temperature rise is confined to the central section of the waveguide (~ 3 cm) so that $\frac{\partial T}{\partial y} \sim 0.5-1$ eV/cm, reversing sign above and below the centerline. The isothermal lines then consist of loops

not concentric with the plasma center but circling around a hot spot just outside the mouth of the waveguide.

We have also determined the equipotential contours from probe measurements after RF turnoff. These data, also given in Fig.3, show that $V_s \sim 6 kT_e$, as one expects from imposing charge neutrality on an argon plasma. The equipotential contours are similar to the isothermal contours, i.e., the potential is a maximum near the center of the waveguide, and falls off horizontally and vertically, such that $E \sim 2V/cm$. The resulting electric field causes the plasma to drift along the equipotential loops at speeds $\sim 5 \times 10^4 cm/sec$ (cE/B) from the bottom to the top of the waveguide. Thus the plasma near the top moves toward the guide, while that at the bottom moves away, causing the point of contact to move up several centimeters in $\sim 20\mu sec$. General flow patterns after short pulse excitation are illustrated in Fig. 4. As the pattern evolves in time the temperature contours (and flow patterns) shift upward and constrict. One expects that most of the plasma near the midplane strikes the upper portion of the waveguide. Thus a "thermosyphon" evolves, in which plasma is pumped from the bottom to the top of the waveguide.

Estimates of the energy flow within the plasma show that electron-ion collisions should extract $\sim 5\%$ of the RF power introduced into the argon plasma column. Initially this power

should heat up the electrons in $\sim 20\mu\text{s}$, consistent with experimental observations. Most of the power is carried away by heat flow parallel to the field lines until the electron temperature exceeds 3-4 eV, when ionization losses predominate. Convective eddies do not contribute significantly to the energy flow except near the waveguide in the region where the density gradient is a maximum.

The flow velocities and surface distortions are greatest near the waveguide. This feature can be readily understood, since the wave power flux, the power absorption by the electrons, the temperature rise, and the space potential gradients are most pronounced in this area. We have measured thermal profiles in cross sections displaced 20 and 40 cm axially from the waveguide. At the 20 cm position the temperature gradients are about one half those measured at the midplane, while those 40 cm away are unmeasurably small. Thus, the undulation extends ~ 20 cm along the plasma after a 1 kW, $20\mu\text{s}$ pulse.

Convective cells have been found in the past to arise in other plasma devices, e.g., in Q machines^{16,17} and magnetic multipoles^{18, 19} subject to asymmetric boundary conditions, but this work appears to be the first identification of such cells in a normally symmetric plasma subjected to asymmetric heating. Such effects are not necessarily restricted to waveguide excitation. Other forms of heating, such as loop excitation of ion cyclotron waves or neutral beam heating of overdense plasmas, may also form thermal eddies under appropriate conditions.

The tenuous surface layers of toroidal plasmas (beyond the limiter) are not qualitatively different from the plasma investigated here, so that thermal eddies might play a role in surface wave excitation. While the higher magnetic fields and higher temperatures would slow down the development of eddies, the much higher power densities (up to 5 kW/cm^2) could easily offset these factors. In the mild form observed in this experiment the eddies could be beneficial. For example, the plasma near the waveguide might be too dense. The eddies, by pumping out some of the surface plasma, might improve the wave coupling and by increasing the recycling rate might produce surface cooling, an effect noticed by Suckewer and Hawryluk²⁰ in ATC.

On the other hand, if eddies are strongly excited, they might produce highly undesirable effects: for example, asymmetric plasma loading of an (open) waveguide might affect the launching angle or the mode structure of the excited plasma waves. The worst possible end result would occur if intense plasma bombardment of the waveguide should lead to copious outgassing and the formation of a constricted high density discharge near the top corner of the guide.

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Fig. 1. Positioning of twin waveguide and probes along argon plasma column.

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 Fig. 2. Vertical scan of the probe ion saturation current following 1 kW, 2.45 GHz pulses of varying duration. From 20 to 80 μsec (not shown) the profile changes only slightly.
 B = 6.1 kG.

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Fig. 3. Vertical scan of the electron temperature and space potential 7 and 17 mm from the waveguide following a 10 μ s pulse of RF power. The space potential V_s was calculated from the measured floating potential through the relation $V_s = V_f + (KT_e/2e) \ln m_i/m_e$. $B = 6.1$ kG.

Flow Pattern

Fig. 4. Flow pattern of convective eddies established near the waveguide by excitation of lower hybrid waves. Immediately opposite the waveguide the flow patterns appear to terminate on the guide.

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