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GENERATION OF PONDEROMOTIVE CRATERS
DURING HIGH POWER MICROWAVE
IRRADIATION OF PLASMA

BY

R. W. MOTLEY, W. M. HOOKE,
AND C. R. GWINN

**PLASMA PHYSICS
LABORATORY**

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Generation of Ponderomotive Craters During High
Power Microwave Irradiation of Plasma

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ABSTRACT

Localized plasma density depressions or craters are observed to form near the mouth of a phased waveguide array, if the power flux exceeds $\sim 0.3 \text{ kW/cm}^2$.

Phased waveguide arrays [1,2] appear to be the most promising method of exciting lower hybrid waves in the surface layers of toroidal plasmas. According to present estimates, it will be necessary to provide a surface power flux of $\sim 5 \text{ kW/cm}^2$ in order to heat the plasma core. At this level the electromagnetic pressure near the mouth of the waveguide becomes comparable to the plasma pressure near the cutoff layer ($\omega \sim \omega_{pe}$), where the electromagnetic fields of the guide convert to slow plasma waves. This possibility has led to predictions that ponderomotive forces will degrade the coupling between the waveguide grill and the surface plasma [3-7].

Nonlinear changes have been observed in the reflectivity of high power waveguide arrays on tokamak plasmas [8-10]. The Petula group [8], for example, has observed an increase in reflectivity from $\sim 5\%$ to 30% as the power level increased to 10 kW/cm^2 . The nonlinear mechanism responsible for the decoupling has not been identified.

RF pressure has been observed to modify the plasma density and the propagation characteristics of electromagnetic and electrostatic waves, in low density, magnetically-confined plasmas [11-12] as well as in laser-produced plasmas [13-15]. In this paper we report the first experimental evidence that plasma cratering, i.e., the creation of a localized density depression, occurs just outside the mouth of a waveguide array driven at high power level. Under certain conditions the formation of craters can reduce the coupling between waveguide and plasma.

In waveguide excitation the most intense electric fields occur just outside the mouth of the guide. In the region between the guide and the cutoff layer the electric field applied parallel to the magnetic field is evanescent. If the density profile is linear, the field varies as [16]

$$E_z^2 = B^2 [Ai^2(v) + Bi^2(v)] \quad (1)$$

where B is a constant, $v = [(n_u^2 - 1)k_o^2 \ell_c^2]^{1/3} (1 - x/\ell_c)$, x is the distance from the waveguide, ℓ_c is the position of the cutoff layer, and $Ai(v)$ and $Bi(v)$ are Airy Functions. Near the cutoff layer the evanescent distance for E_z^2 is

$$\delta = \left[\frac{1}{E_z^2} \frac{\partial E_z^2}{\partial x} \right]^{-1} \approx 1.37 k_o^{-1} / [(n_u^2 - 1)/k_o \ell_c]^{1/3}. \quad (2)$$

For our conditions ($n_u \sim 3$, $\ell_c \approx 1-2$ mm) $\delta = 5.0-6.3$ mm.

The primary effect of the strong, alternating electric field should be to push electrons along the field lines away from regions of high field. The ambipolar potential that develops also forces the ions to move at the sound speed v_i , creating a density depression within a distance $\delta \approx 5$ mm of the waveguide in a time $t_1 \approx z/v_i$, where $z \approx 4$ cm is the axial width of the rf fields. The dynamics can readily be calculated by adding an rf pressure term to the electron equation of motion [7]

$$P_{rf} = nkT_{rf} = \frac{nm_e}{4} \left(\frac{eE_z}{m\omega} \right)^2. \quad (3)$$

After an equilibrium is established the total pressure along the field lines p is a constant

$$p = nkT_e \left(1 + \frac{T_i}{T_e} + \frac{T_{rf}}{T_e} \right) = \text{const.} \quad (4)$$

The equilibrium is maintained with the help of a (positive) ambipolar potential $V = (kT_i/e) \ln n_0/n$; this potential reverses quickly on removal of the rf field (in about one electron transit time $t_2 \approx 50$ nsec) to $V = - (kT_e/e) \ln n_0/n$.

The experiments were carried out in the linear test plasma, H-1 [17], which provides a moderate density ($\sim 10^{12} \text{ cm}^{-3}$) low temperature (1-6 eV) argon plasma 2 m long and 10 cm in diam., confined by a 13 kG magnetic field. A twin, teflon-loaded waveguide positioned at the edge of the plasma column midway between the ends launched up to 8 kW of power at 2.45 GHz into the overdense plasma ($\omega_p^2/\omega^2 \leq 15$). Each element of the waveguide, 2×5.8 cm, was excited in the fundamental TE_{10} mode (E/B_0) [18]. At the highest power level the power flux near the center of the waveguide was $\sim 0.8 \text{ kW km}^2$ and the rf pressure, $E_z^2/8\pi$, was of the same order as the plasma pressure at the cutoff layer ($n_e = 8 \times 10^{10} \text{ cm}^{-3}$, $T_e = 4$ eV).

Horizontal density profiles taken with Langmuir probes above and below the midplane several microseconds after 8 kW rf pulses of varying duration are shown in Fig. 1. The overall effect of the microwave pulse is to raise the electron temperature to 4-6 eV and to increase the electron density by ionization. The ionization rate depends on the background gas

pressure; in the data shown the increase in density was ~25% in 80 μ sec.

Within a few centimeters of the waveguide, however, a more complex readjustment of the plasma equilibrium takes place. In 10-20 μ s a vertical undulation appears in the surface plasma near the guide; the plasma squeezes against the guide near the top and pulls away at the bottom. As shown earlier [19], this new state results from an off center plasma rotation driven by asymmetrical electron heating. Horizontal scanning downstream from the guide shows clearly the development of later stages in the vortex motion, in which high density regions initially at the top rotate around to the bottom and then curl upwards. The net effect near the guide (Fig. 1) is to form a density ridge and plateau, especially noticeable above the midplane ($y = 1.5$ cm).

In this paper, however, we are concerned only with the tenuous plasma within ~5 mm of the guide, the region subjected to the strongest electric fields (up to ~700 V/cm). Measurements of the rf fields (Fig. 1) show that they drop off horizontally in 4 mm, somewhat more sharply than one calculates from Eq. (1) and (2). In this peripheral region we must distinguish between the top and bottom halves of the plasma. Below the midplane two nonlinear effects reduce the plasma concentration-vortex rotation away from the guide and ponderomotive forces. Axial density scans show that the density depression in this region is indeed not localized.

Above the midplane the effects of vortex rotation and ponderomotive pressure oppose one another, so that it is possible to distinguish clearly between the two. Axial scanning 1 cm above the midplane, illustrated in Fig. 2, shows a general elevation of the probe current after a high power pulse, but also a highly localized density depression that extends just beyond the edge of the waveguide. The depression extends radially into the plasma column only ~4 mm and is therefore localized to the region of intense rf fields. It is clear from Fig. 2 that the density crater forms only at the highest power levels (≥ 4 kW). On an absolute basis (from the power flow) we estimate that the electric field E_{z0} at the mouth of the guide is ~700 V/cm and that the perturbation we measure is about twice as great as one calculates from Eq. (3) and (4). A possible explanation of this discrepancy is that the asymmetric plasma load forces E_{z0}^2 to peak more sharply than one assumes, i.e., $\cos^2 \pi y/b$, where b is the vertical guide dimension.

Time-resolved measurements of the density and space potential depressions following a 40 μ s full power pulse are shown in Fig. 3. The crater grows and decays in ~25 μ s, which is about twice the time required for a sound wave to cross the width of the guide ($T_e = 4$ eV). Potential perturbations up to -3.2 volts were measured between the center of the crater and a region displaced 3 cm along the field lines (measurements performed after rf pulse). The solid line in (b) shows that the perturbed density and potential obey the time-dependent Boltzmann relation $n/n_0 = \exp(eV_s/kT_e)$. The

data are therefore consistent with the existence of plasma pressure variations along the magnetic field lines. This check is important, because it rules out the possibility that the changes in the ion saturation current result only from rf biasing of the probe by residual rf fields.

One expects that cratering would reduce the coupling between plasma and waveguide. Experimentally, we find that enhanced reflection does not occur for "normal" operating gas pressures ($2-3 \times 10^{-4}$ torr argon) because the average plasma density rises due to ionization and convection across the field lines, as in Fig. 1 and 2. Below 10^{-4} torr, however, ionization occurs more slowly, so that the average plasma density near the guide drops. This leads to a doubling of the reflectivity from 17 to 35% as the power level rises from 4 to 8 kW. The nonlinear theoretical analysis of the coupling will be mathematically cumbersome, since both axial and vertical symmetry have been disturbed. At present only a one-dimensional nonlinear theory has been developed [6].

The implications of this work are that ponderomotive forces may place an upper limit to the power flux that can be passed through the surface layers of a toroidal plasma. The issue is not clear cut, because the surface conditions, such as the background gas pressure, the amount of recycling, and the electron and ion temperatures, vary significantly from one device to another. In any event, to support a power flux of $\sim 5 \text{ kW/cm}^2$ one will require a plasma pressure $nk(T_i + T_e)$ of at least $2 \times 10^{13} \text{ eV-cm}^{-3}$ within a distance of a few millimeters of the waveguide array.

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Fig. 1. Density profiles near the waveguide taken 1.5 cm above and 1.5 cm below the midplane. Measurements were made several microseconds after 8 kW pulses of varying duration. The curve " E_z " shows the variation of the rf signal on a small electric "T" probe.

Fig. 2. Axial variation of the ion saturation current following 40 μ s, 8 kW rf pulses. The bias voltage was -90 V. The probe was displaced 3 mm horizontally from the guide.

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Fig. 3. Difference in floating potential (a) and the ratio of the ion saturation currents (b) between two probes, one placed near the (horizontal) center of guide, the other displaced 3 cm axially. Both probes were 1 cm above the mid-plane. The Boltzmann relation, shown in the heavy solid line of (b), was calculated from the data in (a).

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