

PLASMA DENSITY PROFILES AND FINITE BANDWIDTH EFFECTS ON ELECTRON HEATING

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MASTER

Intense, p-polarized microwaves are incident on an inhomogeneous plasma in a cylindrical waveguide. Microwaves are mainly absorbed by resonant absorption near the critical surface (where the plasma frequency,  $\omega_{pe}$ , equals the microwave frequency,  $\omega_0$ ). The localized plasma waves strongly modify the plasma density. Step-plateau density profiles or a cavity are created depending on the plasma flow speed. Hot electron production is strongly affected by the microwave bandwidth. The hot electron temperature varies as  $T_H \propto (\Delta\omega/\omega)^{-0.25}$ . As the hot electron temperature decreases with increasing driver bandwidth, the hot electron density increases. This increase is such that the heat flux into the overdense region ( $Q \propto n_H T_H^{3/2}$ ) is nearly constant.

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I. INTRODUCTION

The interaction of intense, p-polarized microwaves ( $E_0^2/8\pi \leq n_e kT_e$ , where  $E_0$  is the amplitude of the incident microwave electric field) is studied experimentally. Measurements were made in the U. C. Davis PROMETHEUS I device. This device models laser absorption due to resonant absorption and parametric instabilities and electron heat transport inhibition due to ion acoustic turbulence. The electrons are essentially collisionless (mean-free-path longer than device dimensions) so that only collective effects are important. The dimensions of the underdense plasma are less than the microwave wavelength, so that electromagnetic instabilities do not occur. The microwave electric field is mainly parallel to the density gradient. Thus, electrostatic waves are driven near the critical surface, resulting in electron heating and resonant absorption. The ponderomotive force due to the waves strongly modifies the plasma density profile.

We report measurements of the ponderomotive force modified density profile and the effect of bandwidth on the heated electrons.

II. EXPERIMENTAL DEVICE

These experiments were performed using the PROMETHEUS I device. A schematic of this device is shown in Fig. 1. A  $TM_{01}$  mode ( $\omega_0/2\pi=1.2$  GHz) is dominantly excited in an evacuated cylindrical waveguide (left chamber). A thin ceramic sheet confines a discharge plasma to the right chamber but allows free transport of the microwaves. The plasma density increases with distance from the ceramic

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sheet due to the nonuniform tungsten filaments (cathode) which emit the ionizing electrons. The p-polarized microwaves drive electrostatic waves up at the critical density, and electrons are heated. Most of the heated electrons are reflected at the ceramic sheet. The anode (right end of the chamber) maintains the plasma potential 35 V positive relative to the cylindrical waveguide walls. Thus, most of the heated electrons are reflected near the cylindrical wall and travel toward the anode. This device then models the critical region and the corona in a laser driven pellet. The argon gas pressure is typically  $0.3$  to  $0.5 \times 10^{-3}$  Torr ( $n_n > 10^{13} \text{ cm}^{-3}$ ), the critical density  $n_c = 1.8 \times 10^{10}$ , and the initial (without microwaves) electron temperature  $T_{e0} = 1.3$  to  $1.5$  eV (or  $\lambda_{De} \approx 10^{-2}$  cm), so that the electron-ion and electron-neutral mean-free-path is much greater than all important lengths ( $\lambda_{ei} = \lambda_{en} \approx 100$  cm). The maximum microwave power available is 12 kW, which corresponds to  $v_{os}/v_{e0} \approx 1$  ( $v_{os} = eE_0/m\omega_0$ ). The microwaves are pulsed with a pulse length which is short enough so that the microwaves or the heated electrons do not cause significant ionization of the neutral gas ( $\tau_M \leq 10$   $\mu\text{sec}$  (or  $\tau_M \omega_{pi} \leq 240$ ) at low power and  $\tau_M \leq 2$   $\mu\text{sec}$  at very high power). Tiny ( $d \leq \lambda_{De}$ ) coaxial Langmuir probes are used to measure the plasma density. Thus, the plasma density cannot change significantly. The density is measured a short time ( $\approx 0.5$   $\mu\text{sec}$ ) after the microwaves are turned off, so the microwaves do not affect the measurement. One-sided, planar Langmuir probes are used to measure the heated electron energy distribution in the overdense region.

### III. PLASMA DENSITY PROFILES

We have measured the interaction of p-polarized microwaves with an inhomogeneous plasma in space and time. The plasma density profiles are given in Fig. 2 as a function of microwave power,  $P_0$ . The measurements are made after the microwave pulse has been on long enough ( $\omega_{pe} t \approx 3 \times 10^4$ ) so that apparently asymptotic profiles are measured. The plasma density is strongly modified near the critical surface. The density gradient scale length,  $L = -[(dn/dx)/n]^{-1}$ , decreases with  $P_0$  (Fig. 2(a)-(c)). The step-plateau-like density profile is observed (Fig. 2(c) gives  $50 \lambda_{De0}$  for the scale length). The scale length increases with  $P_0$  for high microwave powers ( $P_0 > 0.2$  kW). The scale length agrees very closely with the scaling law derived from simulation calculations for the weak power regime and does not agree<sup>2</sup> with the simulation results for the strong power regime, where strong thermal electron heating is observed (Fig. 3).

No cavity is observed after long times into the pulse ( $\omega_{pe} t = 3 \times 10^4$ ) except for very low power microwave irradiation<sup>3</sup>. However, the density profile is quite different from the above results, and a narrow and deep cavity is produced even for intense microwave irradiation when the flow speed is close to the sound speed.

Fig. 4 gives the time evolution of the plasma density profile. The width and the depth of the cavity grow with time. The width is as small as  $10 \lambda_{De}$ , and the depth,  $\Delta n/n$ , is about 0.45 at  $\omega_{pe} t = 3 \times 10^4$ . A high frequency field is observed to be trapped in the cavity.

#### IV. FINITE BANDWIDTH EFFECTS ON ELECTRON HEATING

We have used a solid state amplifier to produce a broadband driver ( $\Delta\omega/\omega \leq .01$ ) at 1.2 GHz. We have measured the hot electron production from resonant absorption. More than one hundred samples are collected and averaged using a computerized (LSI-11) data acquisition system. The results are presented in Fig. 5. The hot electron temperature ( $T_H$ ) decreases with  $\Delta\omega$  (solid circles in Fig. 5), while the hot electron density ( $n_H$ ) increases with  $\Delta\omega$  (open circles). The hot electron temperature increases with bandwidth of the microwaves as  $T_H \propto (\Delta\omega/\omega)^{-0.25}$ . The hot density increases so that the heat flux ( $Q \propto n_H T_H^{3/2}$ ) is nearly constant. We also observed that the absorbed microwave power is nearly constant as a function of bandwidth.

#### V. CONCLUSION

In conclusion, we find that the plasma flow velocity is important in determining the plasma density profile near the critical surface. Profiles other than the usual step-plateau are observed at higher flow speeds. We also find that driver bandwidth strongly affects the heated electron temperature due to resonant absorption. We find that  $T_H \propto (\Delta\omega/\omega)^{-0.25}$ . This effect<sup>4</sup> may allow drivers to be chosen to limit the production of suprathermal electrons.

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PROMETHEUS  
EXPERIMENTAL SCHEMATIC

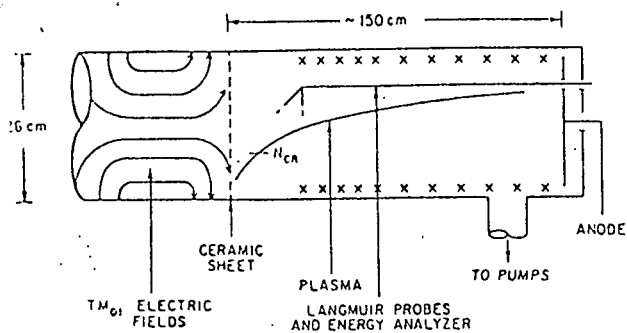


Fig. 1 Schematic diagram of apparatus.

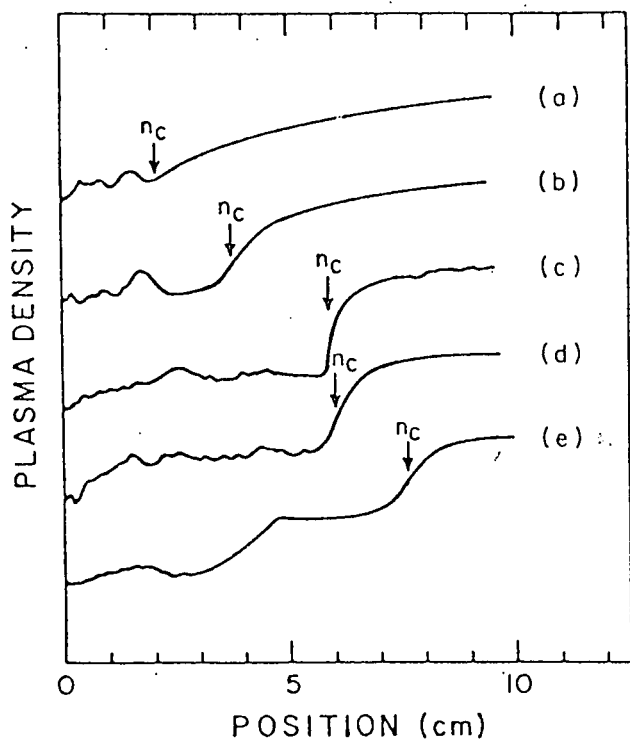


Fig. 2 Plasma density profiles:  
a)  $P_0=10W$ ; b)  $40W$ ; c)  $160W$ ;  
d)  $200W$ ; e)  $2kW$ .

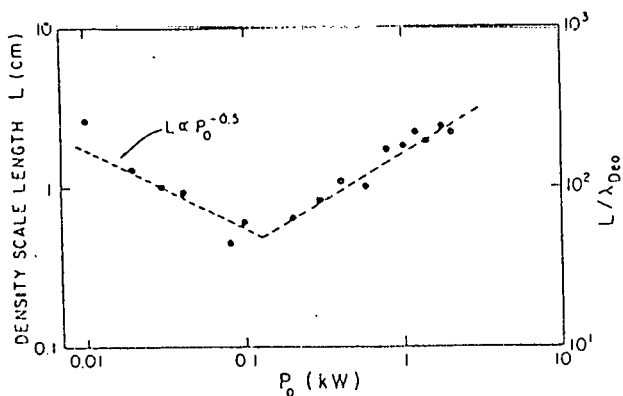


Fig. 3 Density scale length vs.  $P_0$ .

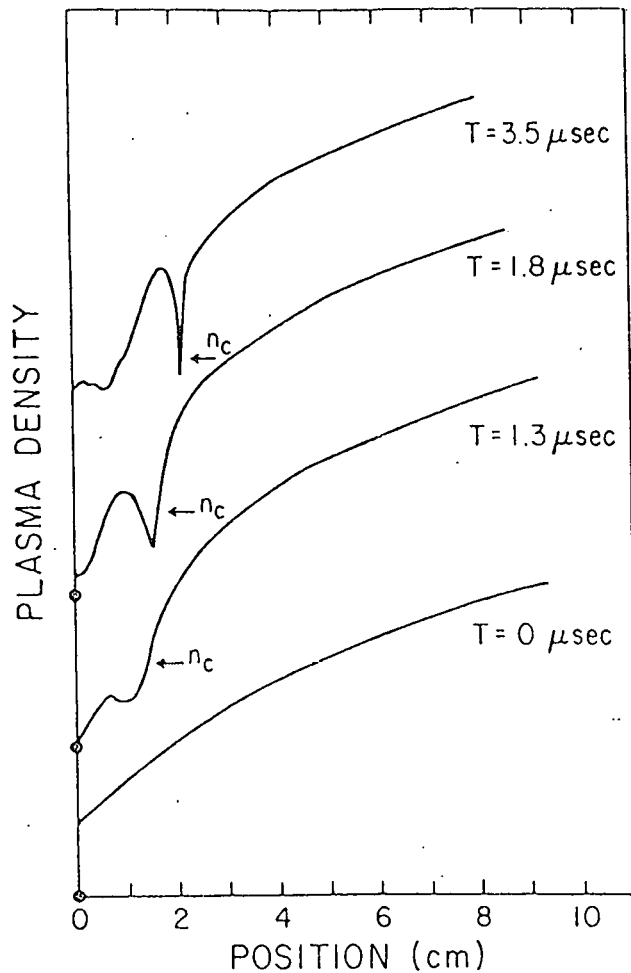


Fig. 4 Time evolution of plasma density profile.  $P_0=1kW$ .

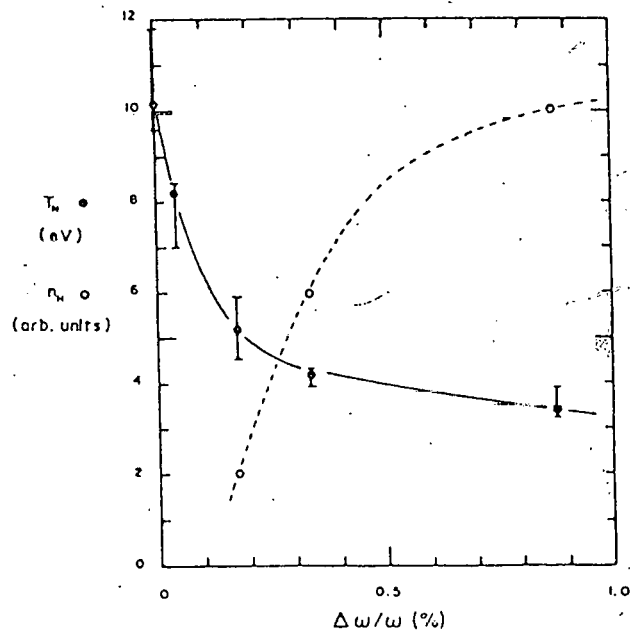


Fig. 5 Hot electron temperature and density vs. microwave bandwidth.  $P_0=200W$ .