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LOWER-HYBRID HEATING AND CURRENT DRIVE IN TOKAMAKS AND RELATED EXPERIMENTS

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LOWER-HYBRID HEATING AND CURRENT DRIVE IN TOKAMAKS AND RELATED EXPERIMENTS

Abstract

Experimental results on waveguide-plasma coupling and rf heating in the vicinity of the lower-hybrid frequency in the M.I.T. Alcator-A and in Versator II tokamaks are reported. The forthcoming Alcator-C lower-hybrid heating experimental parameters are summarized. From Princeton results on several small-scale experiments, related to waveguide-plasma coupling (H-1) and rf current drive (ACT-1), are presented, as well as recent theoretical investigations of efficient rf current generation using lower-hybrid waves or Alfven waves.

1. M.I.T. ALCATOR-A AND ALCATOR-C EXPERIMENTS.

Up to 90 kW of microwave power has been injected into the Alcator A tokamak at a frequency f = 2.45 GHz which is in the lower-hybrid frequency range [1]. A double waveguide array was employed, each waveguide having inner dimensions of 1.275 cm x 8.13 cm and they were separated by a 1 mm septum. Both rf phase and amplitude could be controlled independently in each waveguide, and the radial position of the waveguide mouth was adjustable. The ceramic vacuum windows in the waveguides were located ouside the toroidal field magnet so that the $\omega = \omega_{ce}$ layer was situated in vacuum.

Optimized coupling and reflectivities of 10% to 15% were obtained with the waveguide mouth positioned near the vacuum vessel wall and with 0, π phasing of the incident electric fields in the two waveguides. This reflectivity remained unchanged up to the full power level of 90 kW, which corresponded to an intensity at the waveguide mouth of 4.5 kW/cm^2.

During rf injection at the 90 kW level, a factor of 50 increase in the fusion neutron rate was observed in a deuterium plasma in which $\bar{n}_e \approx 1.7 \times 10^{14}$ cm^{-8}, B_T = 62 kG, and $I_p \approx$ 150 kA, as shown in Figure 1a. No increase in plasma voltage or impurity emission occurred. A spatially resolved neutron detector indicated that this neutron emission was localized to the center of the Alcator A plasma. Charge exchange measurements indicated that this neutron rate was caused by the formation of an energetic ion tail at the plasma center. The 2.5 - 2.0 msec decay times of the neutron rate after rf shutdown imply that the energetic tail is characterized by a temperature $T_T > 10$ keV and that this tail persists out to an energy $E_T > 50$ keV [2]. This energetic tail exhibits the expected influence of banana orbit ion confinement on neutron production: no rf-produced neutron enhancement is observed at $I_p < 100$ kA and the neutron rate decay time increases by a factor of 2 when I_p is raised from 120kA to 200 kA. Furthermore, the observed presence of a velocity space loss region due to ripple trapping [3] is expected to contribute to the loss rate of the rf-produced ion tail [2]. The estimated ion heating efficiency is less than 40% in the present experiments.

Figure 1b shows the neutron rate enhancement vs. $\bar{n}_e$; the sharp band in $\bar{n}_e$ within which there is a neutron enhancement occurs at a lower density than expected for the value of $k_\parallel = \vec{k} \cdot \vec{B}/|B| \sim 3\ \omega/c$ that should characterize the emitted lower hybrid wave spectrum. Furthermore, changing the relative phasing of the two waveguides to 0, 0 from 0, π did not affect the rf enhanced neutron rate. When the density was reduced below this neutron production density band, a 10% increase in T_e was observed. The heating efficiency in the electron heating mode is at least 35% (and possibly much higher). Electron heating due to electron Landau damping would require $k_\parallel \gtrsim 5\ \omega/c$ for $T_e = 1$ keV. These heating results imply a modification in the wave vector spectrum at the plasma edge from that of linear theory so as to enhance the higher $k_\parallel$ components. Furthermore, rf probe spectra obtained at the plasma edge showed that the pump wave frequency was broadened by 0.5 to 6 MHz and comparably downshifted; these spectra were waveguide phase independent.

Using CO_2 laser scattering, the driven lower-hybrid waves have been studied directly in the plasma interior [4]. The measured wave amplitude $\tilde{n}_e^2$ was proportional to the net transmitted power P into the plasma, but was independent of waveguide phasing, for $0.4 \leq P \leq 4$ kW/cm^2. By measuring the wave amplitude as a function of $k_\perp = 2\pi/\lambda$ and using the lower hybrid dispersion relation, the $n_\parallel$ spectrum was deduced. A broad $n_\parallel$ spectrum $P(n_\parallel)$ was observed with highest amplitudes at the lowest $n_\parallel$ in the range $3 \leq n_\parallel \leq 8$. The waves observed in the range of densities $5 \times 10^{13} \leq \bar{n} \lesssim 1.5 \times 10^{14}$ cm^{-3} were not localized into resonance cones. They have a frequency width $\Delta\nu$ ($0 \leq \Delta\nu \leq 8$ MHz FWHM), which is independent of P and increases with plasma density, and are downshifted from the driving frequency by an amount $\lesssim 1.5$ MHz, with the largest downshift at the highest density. Finally, $P(n_\parallel)$ decreases rapidly as a function of density at all observed $n_\parallel$'s for $\bar{n} \gtrsim 1.5 \times 10^{14}$ cm^{-3}.

There are several mechanisms which could explain the foregoing results: (1) scattering of lower-hybrid waves from long parallel wavelength density fluctuations previously observed near the edge of the Alcator-A plasma column [5] and their subsequent modification by shear [2,6], parametric decay [2], and toroidal effects [6].

We are beginning a new series of high-power lower-hybrid heating experiments in Alcator-C. The parameters will as be as follows: $B \simeq 10T$, $n = (4\text{-}10) \times 10^{14} cm^{-3}$, $f_0 = 4.6$ GHz, $P \lesssim 4.0$ MW, $\tau_{pulse} \lesssim 0.5$ sec. The power will be injected into Alcator-C through four ports, each having a grill with a 4 × 4 waveguide array. The phase of each waveguide can be varied electronically during the rf pulse. The ceramic windows (BeO) will be brazed into the waveguides so that the $\omega = \omega_{ce}$ layer will be pressurized in the waveguide.

2. VERSATOR II EXPERIMENTS

Using a four-waveguide array, we are studying ion heating near the lower-hybrid frequency, and using a six-waveguide array we are studying electron heating and current drive in the M.I.T. Versator II tokamak ($R = 40$ cm, $a = 13$ cm, $B_T \simeq 1.2\text{-}1.5$ T, $I_p \lesssim 40$ kA, $T_{eo} \lesssim 600$ eV, $n_o = (1\text{-}4) \times 10^{13} cm^{-3}$). Coupling experiments at power-levels $P = 1\text{-}10$ kW, $S = P/A = 1\text{-}20$ W/cm^2, show that the reflected power is strongly dependent on the relative phases $\Delta\phi$ of the guides, as well as on the grill radial position. The results for the four-waveguide grill (gap width 2.45 cm, wall thickness is 0.6 cm) are shown in Figure 2. In the theoretical curves (based on the Brambilla code [7]) we used the density gradients measured by Langmuir probes at the plasma edge ($\nabla n \simeq 10^{10}\text{-}10^{11} cm^{-4}$) in the absence of rf power. We see that there are considerable discrepancies between the experimentally measured reflection coefficients and the theoretical predictions. If we assume a density gradient 50-100 times larger than the measured values, we get a reasonable agreement with the average reflection coefficient. However, the relative magnitude of the reflection coefficients between inner and outer waveguides is still reversed from that predicted by theory. Similar disagreement is found in low power experiments utilizing the six-waveguide grill. At present, these results are not well understood.

We have also begun high power experiments ($P = 10\text{-}60$ kW, $P/A = 100\text{-}600$ W/cm^2) in which case we observe a transition to a regime characterized by phase-independent reflection coefficients at power levels $P/A = 400$ W/cm^2. Further high power ($P \lesssim 100$ kW) heating and current drive studies have just begun.

3. THEORETICAL AND EXPERIMENTAL RESULTS FROM PRINCETON

In using rf-driven currents for steady-state reactor operation, the crucial concern is the minimization of the power dissipation. This points to utilizing either lower-hybrid waves [8] which transfer their momentum to nearly collisionless electrons, or Alfven waves which have high momentum content [9].

Current generation by means of lower-hybrid waves has now been observed in the ACT-1 toroidal device [10]. The waves are driven by slow-wave structures which are energized 90° out of phase with each other, giving rise to waves traveling predominantly in one direction. Currents of up to 10 A have been generated by 500 W of rf power at 160 MHz. The current direction changes with the wave direction as expected. Numerical studies [11] show the power dissipation to be a factor of 1.7 less than initial analytic estimates [8]. The new estimates, which are based on the solution of the two-dimensional (in velocity space) Fokker-Planck equation with an added quasilinear diffusion term due to the waves, enhance the attractiveness of the lower-hybrid current-drive scheme for tokamak reactors.

Ponderomotive force effects on lower-hybrid wave coupling and propagation is the concern of related theoretical and experimental work. Theoretical studies of the waveguide coupling including the nonlinear effects indicate a decreased sensitivity of the reflectivity to the waveguide phasing at high power [12]. In the L-3 linear device, when $E^2/8\pi nT \sim O(1)$ at the plasma surface, the wave coupling efficiency deteriorates [13]. Also observed are density modifications which change the wave trajectory [14].

Ponderomotive effects were also studied in the H-1 linear device where 5-60 μs burst of power from an 8 kW, 2.45 GHz magnetron were applied to an overdense linear test plasma ($\omega_p^2/\omega^2 \sim 15$, B = 13 kG) by a twin waveguide.

At moderate argon pressure (2×10^{-4} torr) the waveguide reflectivity (180°) rises from $\sim$ 5% to 12% within $\sim$ 20 μs. This moderate increase occurs because the plasma pulls away from the guide by 5-10 mm as a result of a cross-field vortex motion centered 0-1 cm from the guide mouth [15].

At low pressure and high power (> 4 kW $\equiv 0.4$ kW/cm^2) a localized ponderomotive cavity forms within 6 mm of the mouth of the guide (Figure 3). The guide reflection then rises to $\sim$ 40% and is independent of the phase of excitation. Similar behavior is to be expected in tokamak experiments at 5 kW/cm^2 if the plasma pressure is $< 3 \times 10^{13}$ eV cm^{-3} within a distance of $\sim k_{\parallel}^{-1}$ of the waveguide.

Two experiments on the parametric decay of lower hybrid waves have been carried out. One involved parametric decay into a lower hybrid wave and an ion-acoustic wave in which convective losses are predominant [16]. Another experiment involved parametric decay into a lower hybrid wave and a non-resonant ion quasi-mode which occurs at $\omega \sim \omega_{pi}$. Strong ion heating is observed with this decay. The decay thresholds measured in both experiments are in good agreement with theory.

Parametric decays, however, are not expected to affect the efficiency of lower-hybrid current-drive under reactor conditions [8]. Numerical calculations show that for reactors the current-drive efficiency is, similarly, negligibly influenced by the nonlinear effect of wave-particle resonance broadening [17].

Numerical studies of current generation by Alfven waves, similar to the studies on lower-hybrid waves, show that suitably chosen Alfven waves can incur less power dissipation than lower-hybrid waves [18]. It is assumed here that only the compressional Alfven wave is excited. Coupling to the shear Alfven resonance [19] is shown to be negligible. In the 10 keV temperature range and assuming $\beta > 5\%$, Alfven waves can drive currents using less than half the power required for lower-hybrid waves. In the 20 keV temperature range, the accessibility condition on lower-hybrid waves becomes more severe with the consequence that Alfven waves become relatively more attractive. Nevertheless, for continuous reactor operation, lower hybrid waves may still be preferred for generating currents because they may be injected by means of waveguides, which withstand reactor conditions better than coils do.

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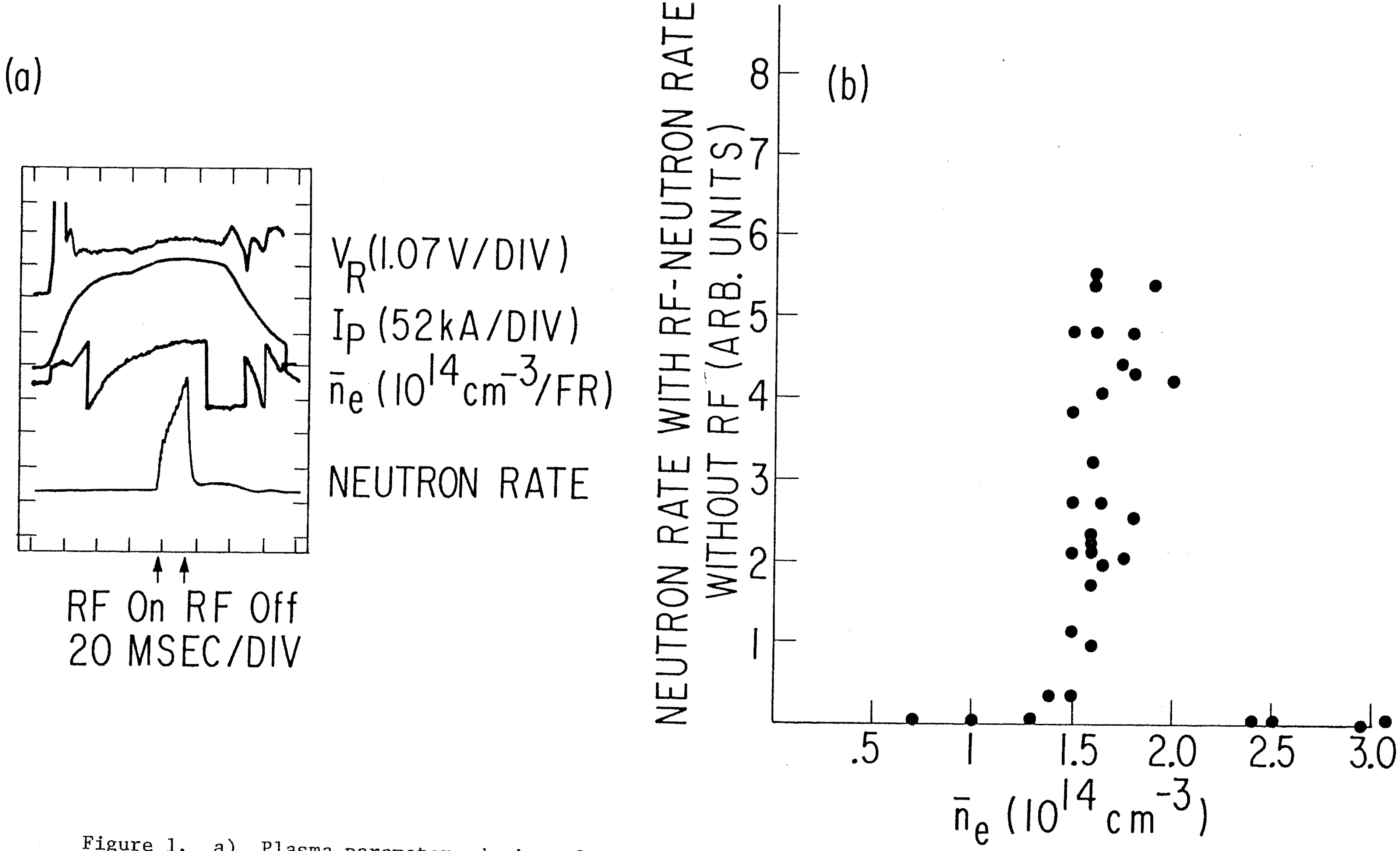
FIGURE CAPTIONS

Figure 1. a) Plasma parameters during rf injection in Alcator A; B_T = 62 kG, P_{rf} = 90 kW, deuterium gas fill, and the waveguides are phased 0, π.
b) Neutron rate enhancements from several shots vs $\bar{n}_e$ for the same parameters as (a) and I_p = 150kA.

Figure 2. Experimental and theoretical reflectivity in the Versator II four-waveguide experiment. The phasing of the four waveguides is 0, π, 0, π. The plasma chamber lies to the left of X = 0, and to the right the grill is retracted into the port.

Figure 3. Rf signal ($\propto E_z^2$) and density 2 mm from mouth of guide during 8 kW rf pulses. Dashed lines show position of waveguide walls.



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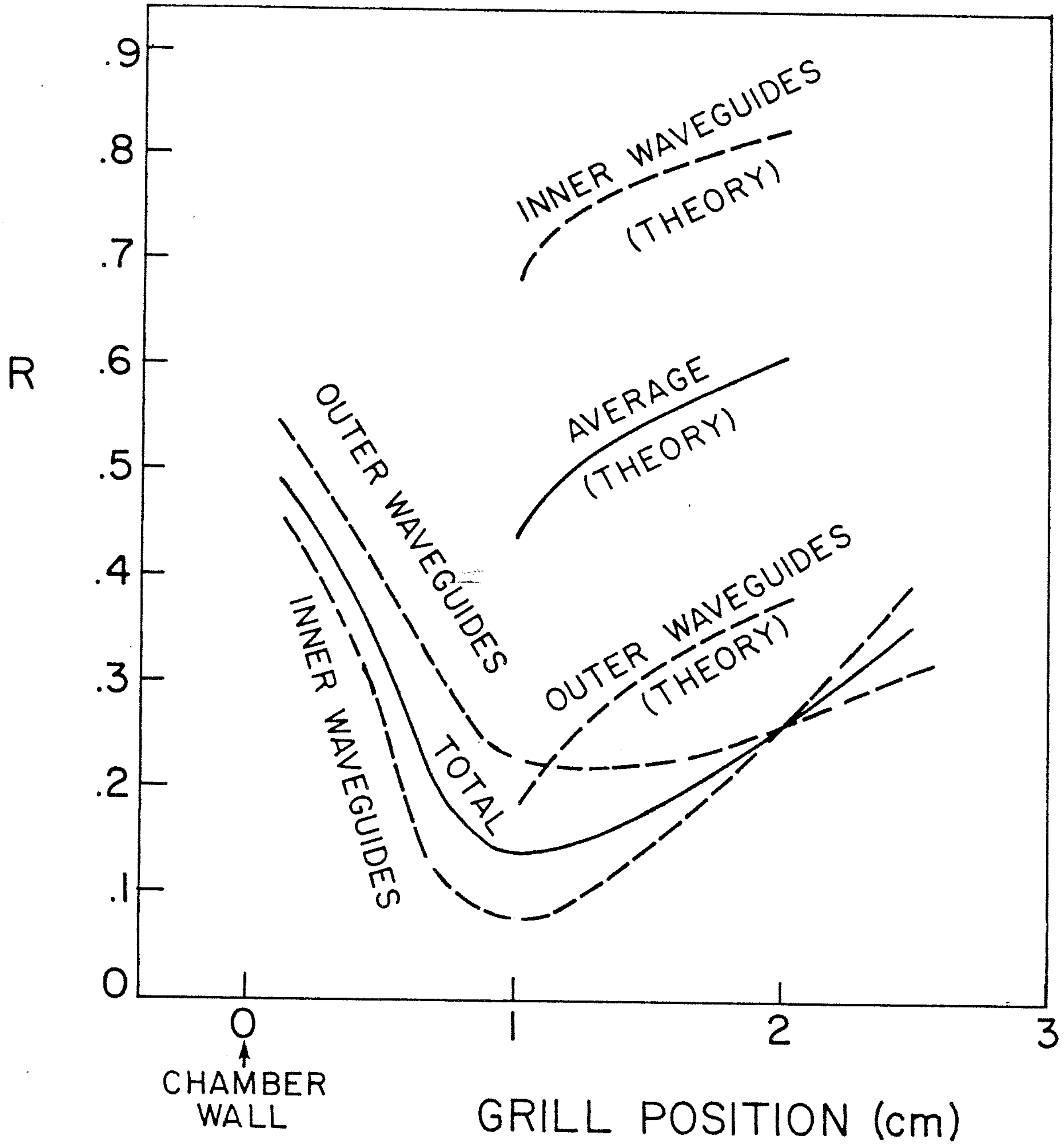

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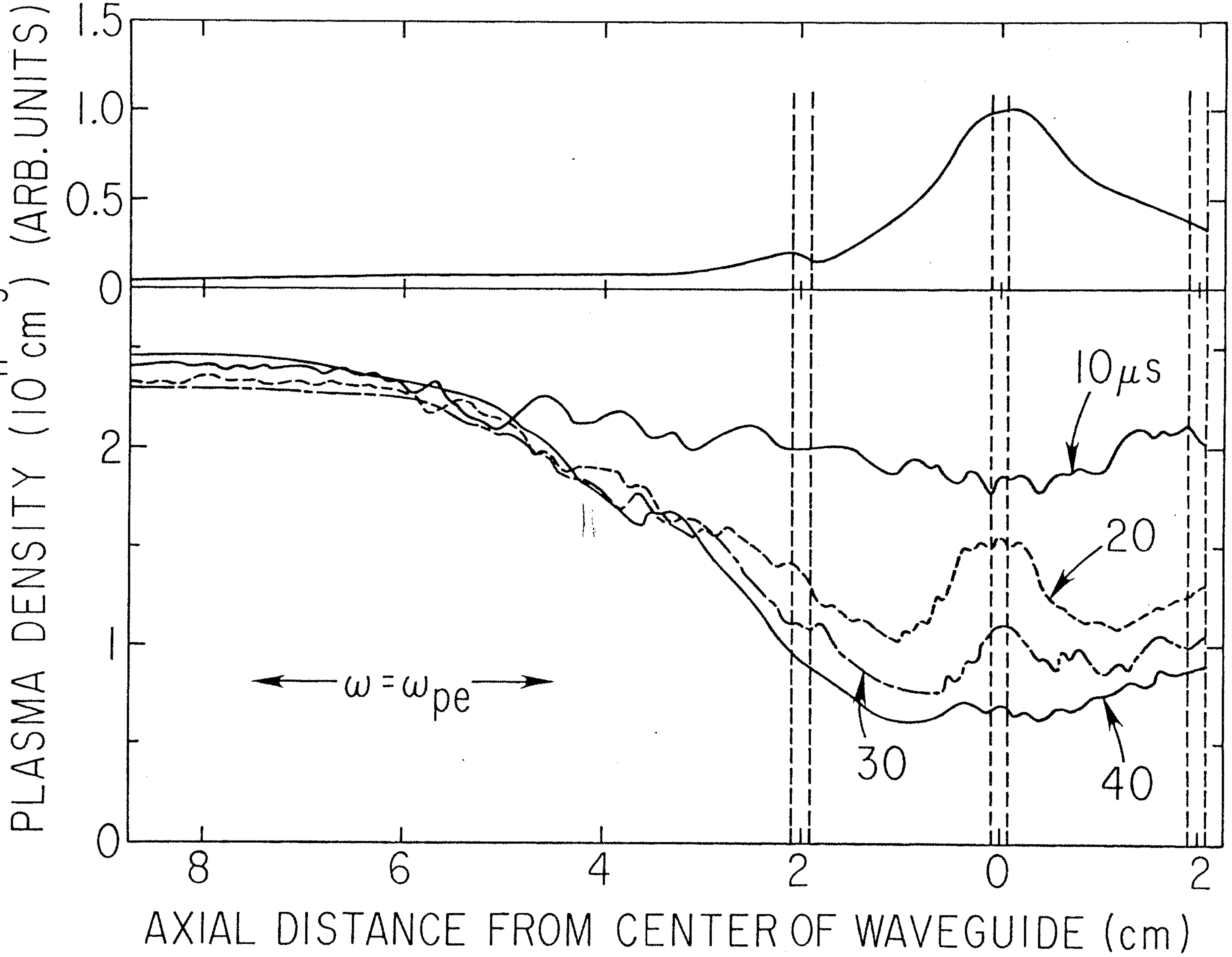

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