sity of completely stripped oxygen ions are not known.

In conclusion, radial profiles of low-ionization-degree impurity ions and of highly ionized ions have been obtained. We have shown that these profiles can be used in order to deduce impurity fluxes and that the values obtained for the oxygen ions *in the outer plasma shell* agree reasonably well with the theoretical ones. It must be pointed out, however, that, from particle- and energy-balance considerations, it has been previously shown that these large fluxes cannot reach the plasma center.[3]

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Effects of Finite-Bandwidth Driver Pumps on the Parametric-Decay Instability*

S. P. Obenschain, N. C. Luhmann, Jr., and P. T. Greiling
University of California, Los Angeles, California 90024
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The effects of a finite-bandwidth driver pump on the parametric-decay instability are investigated experimentally. The results include the dependence of threshold power, growth rate, and saturation level on the bandwidth of several coherently and randomly modulated pumps.

Parametic instabilities of both the absorptive and reflective types may have serious consequences for laser-pellet fusion and laser or rf heating of magnetically confined plasmas. There has therefore been considerable interest in means to increase the instability thresholds and reduce the growth rates. A proposed solution is to properly shape the bandwidth characteristics of the pump.[1-5] Theoretical investigations[1,4] indicate that for the case of a randomly modulated pump whose energy is uniformly distributed over a bandwidth $\Delta\omega$ much larger than the instability resonance width γ, the effective power available to excite the instability is related to the incident power P_0 by $P_{\rm eff}=\gamma/\Delta\omega P_0$. In this large-bandwidth limit ($\Delta\omega \gg \gamma$), the precise mechanism responsible for producing the finite-bandwidth pump has been found to be rather unimportant in terms of the effects on threshold and growth rate.[1] In the present discussion the effective power is defined to be that fraction of the spectral energy distribution of the pump contained within the instability resonance width. This definition provides a means to compare pumps with various continuous as well as discrete spectral distributions. A simple extension of present theory therefore suggests that the effective power as defined above should determine the threshold, growth rate, and saturation level regardless of the bandwidth mechanism. It should be noted, however, that the resonance width increases with increasing pump power and plasma inhomogeneity, so that for laser-pellet interactions the realizable widths may be more nearly comparable ($\Delta\omega \simeq \gamma$). In this case, one expects the particular bandwidth mechanism to be important. For the experiment described herein, we employed several distinctively different finite-bandwidth mechanisms to explore the effect on the decay instability.

The experiments were performed in an unmagnetized, electrostatically confined, filament-discharge plasma[6] of 100 cm length and 35 cm diam with argon fill pressures of 0.4 mTorr. Typical plasma parameters are electron temperature $kT_e \simeq 2-3$ eV, temperature ratio $T_e/T_i \simeq 8-10$, plasma density $n_e = (2-18)\times 10^9$ cm^{-3}, and total background fluctuation level $\Delta n/n < 0.1\%$. The rf driver pump (frequency $\omega_0 > \omega_{pe}$) is introduced by means of a gridded parallel-plate capacitor system (5 cm diam grids with 3 cm spacing) similar to that of Stenzel and Wong.[7] Plasma density and temperature are monitored using both Langmuir probes and a retarding-grid electrostatic energy analyzer. Movable shielded double probes are used to detect the excited ion waves; the high-frequency decay waves are monitored by coaxial probes shielded from direct rf pickup. Upon application of rf power to the grids, a well-defined ion disturbance ($\Omega_i/2\pi \simeq 400$ kHz) appears when the power exceeds a distinct threshold value. The ion fluctuations are accompanied by high-frequency sideband decay waves ω_e. The observed value of the threshold power together with frequency matching ($\omega_0 = \omega_e + \Omega_i$) and phase-velocity measurements indicate that the parametric decay instability is excited by the pump.

The resonance width of the instability, as determined by a narrow-band pump, is typically ~ 1% of the pump center frequency. Here the resonance width is defined as the full width of the threshold power curve at the twice-power points. This observed width is much larger than that calculated from uniform plasma theory ($\lesssim 0.1\%$) and is due, we believe, to the gentle density gradients (~ 2%/cm over several centimeters) produced by the insertion of the grids into our otherwise uniform plasma and to the finite-size interaction region.

Several different finite-bandwidth pumps are employed in this experiment. By mixing narrow-band rf with white Gaussian noise in a balanced mixer, rf of adjustable bandwidth is produced, where the bandwidth arises from both amplitude and phase modulation. Another source produces a pump whose bandwidth is primarily due to phase modulation. The rf field of this source is given by $E(t) = \cos[\omega_0 t + \alpha(t)]$, where $\alpha(t)$ is the particular phase modulation function. The pure phase-modulation results reported herein are concerned with either the case of coherent sinusoidal phase modulation, with $\alpha(t) = x\cos(\omega_m t)$, where ω_m is the modulation frequency and x the modulation index, or the case of random-noise phase modulation. The noise modulation employed is Gaussian white noise of adjustable amplitude and bandwidth.

For the case of sinusoidal phase modulation, the rf field may be expanded in terms of Bessel functions. Its Fourier spectrum then consists of the fundamental with amplitude proportional to $J_0(x)$ and modulation sidebands of amplitude $J_n(x)$ and frequency $\omega = \omega_0 \pm n\omega_m$, where n is an integer. When $\omega_m \gg \gamma$ and ω_0 has been adjusted to coincide with the frequency for minimum threshold, the effective power $P_{\rm eff}$ is just $J_0^2(x)P_0$. Theory[4] therefore predicts the threshold power to be a function of the modulation index:

$$P_{\rm thres}(x) = J_0^{-2}(x)P_{\rm thres}(0).$$

In Fig. 1(a), the experimentally determined threshold power normalized to the narrow-band threshold is plotted as a function of the modula-

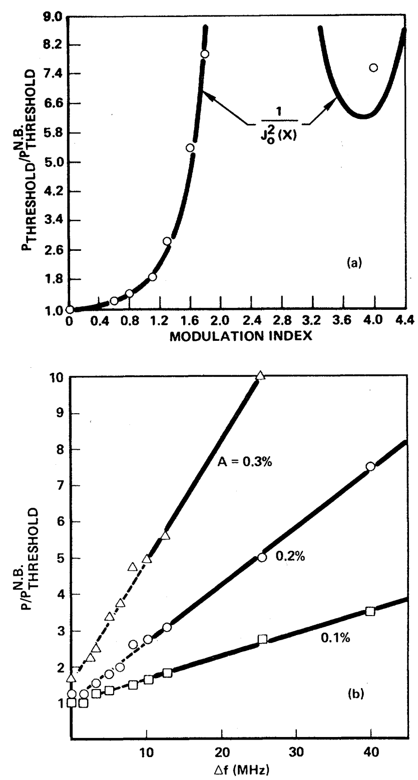

FIG. 1. (a) Threshold power normalized to the narrow-band threshold as a function of modulation index for a sinusoidally phase-modulation pump ($\omega_m > \gamma$). (b) Pump power (normalized to the narrow-band threshold) required to produce a given density-fluctuation level A as a function of the width of the balanced-mixer-produced noise pump.

tion index for the case $\omega_m \gg \gamma$. Note the agreement between theory and experiment, even at large modulation index, including a point within the second cycle of the Bessel function.

Figure 1(b) illustrates similar results for the balanced-mixer-produced noise pump. In this case, the power necessary to achieve a given normalized density-fluctuation amplitude A is plotted as a function of the pump bandwidth $\Delta f = \Delta\omega/2\pi$. Here A is defined by $A = (n_i T)^{-1}\int_0^T |\Delta n_i| \times dt$, where T is large compared to the wave growth times and Δn_i is the total density-fluctuation level in the frequency range of the parametric-decay-instability produced ion waves [~0.1–1 MHz]. The lowest amplitude, $A = 0.1\%$, corresponds to the threshold level where the instability first appears distinctively above the background fluctuations. In the limit $\Delta\omega \gg \gamma$, theory[1,4] predicts that for the threshold power and pump bandwidth $\Delta\omega$ are linearly related. Over the range of power levels and bandwidths investigated, this relation was found to be approximately satisfied not only for the instability threshold power, but also for the power necessary to achieve a given level of saturated density fluctuations. The straight line fit to the data presented in Fig. 1(b) is evidence of the validity of the theory. The nonzero intercept of the lines for $\Delta\omega = 0$ is indicative of the limitations of the theory which does not take account of the precise interaction of the pump at frequencies outside the resonance region. An estimate of the instability resonance width at each fluctuation level may be obtained from the slope of the lines in Fig. 1(b). Alternatively, the resonance width may be obtained directly by varying the frequency of the narrow-band pump and observing the width of the instability curve at the twice-power points for a given fluctuation level. The results obtained from both techniques are compared in Table I and are found to be in reasonable agreement. Similar results were obtained for the purely phase-modulated noise pump.

Detailed studies of the saturated level of the instability as a function of pump center frequency, power, and bandwidth were also made. In Figs. 2 and 3, experimental scans of the normalized density-fluctuation level A are displayed as a function of pump frequency and power for both noise and sinusoidally phase modulated pumps. The width $\Delta\omega/\omega_0$ of the noise phase-modulated pump is varied from ~0% to 1.2% in Fig. 2, while the pump power is increased from 0.5 to 2 W in 0.5 W increments. Increased thresholds and decreased saturated levels are evident as the bandwidth is increased beyond the instability resonance width. Results of measurements of saturated density-fluctuation levels obtained by successively increasing the modulation index of the sinusoidally phase-modulated pump ($\omega_m > \gamma$) are shown in Fig. 3. In this case only the results from two pump power levels are displayed. These latter results clearly illustrate that while coherent pump modulation can increase the threshold

TABLE I. Instability resonance width $\Delta\omega/2\pi$.

Fluctuation level (%)	Resonance width[a] (MHz)	Resonance width[b] (MHz)
0.1	25	16
0.2	14	8
0.3	8	6

[a]Resonance width determined using narrow-band pump.

[b]Resonance width obtained from slopes in Fig. 1(b).

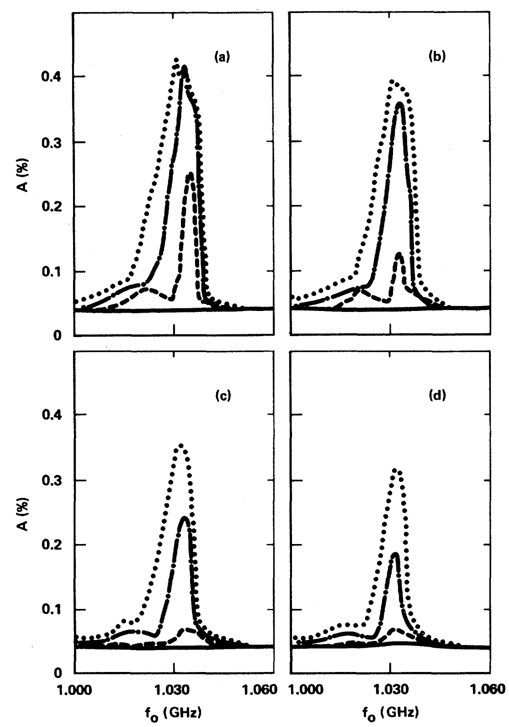

FIG. 2. Saturated density fluctuation level A as a function of pump power and center frequency for the noise phase-modulated pump. The noise bandwidth $\Delta\omega/2\pi$ is < 10 kHz for (a), 3 MHz for (b), 6 MHz for (c), and 12 MHz for (d). Pump power is varied from 0.5 to 2.0 W: —, 0.5 W; - - -, 1.0 W; -·-, 1.5 W; and ···, 2.0 W.

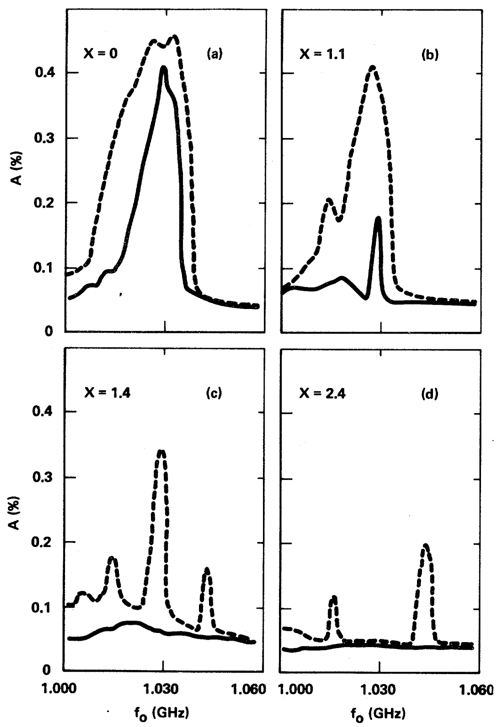

FIG. 3. Saturated density-fluctuation level A as a function of pump power and center frequency for the sinusoidally phase-modulated pump ($\omega_m/2\pi = 14$ MHz $> \gamma/2\pi$). The modulation index is $x = 0$ for (a), $x = 1.1$ for (b), $x = 1.4$ for (c), and $x = 2.4$ for (d). For $x = 1.4$ the pump power is distributed approximately equally between the center frequency and the first upper and lower modulation sidebands, while for $x = 2.4$ the power at the center frequency is approximately zero. Two values of pump power are shown: —, 2.0 W, and - - -, 4.0 W.

and decrease the saturation level for pumps tuned to threshold minimum, it can have the opposite effect at multiples of the modulation frequency.

The instability growth rate dependence upon bandwidth was also investigated. The results were consistent with predictions in that the instability behaves as if only the power contained within the resonance width were applied.

When the pump bandwidth $\Delta\omega$ becomes comparable to γ, we find little change in the instability threshold, growth rate, and saturation level from the narrow-band case. However, there does appear to be a change in the instability mechanism. For the case of sinusoidal phase modulation with $\omega_m \lesssim \gamma$, each of the main spectral components of the pump can have decay sidebands, indicating a higher-order bootstrapping process. These additional sidebands are not observed for $\omega_m \gg \gamma$. Details of the region $\Delta\omega \lesssim \gamma$ will be presented elsewhere.

In conclusion, our results for wide-bandwidth pumps ($\Delta\omega \gg \gamma$) are consistent with theoretical predictions. Interesting effects occur for narrower bandwidths, and further theoretical and experimental investigations appear justified.

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