Relativistic plasma microwave electronics: Studies of high-power plasma-filled backward-wave oscillators*

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The area of relativistic plasma microwave electronics has only recently generated renewed interest. New experimental data are presented demonstrating that the presence of a low-density background plasma in a relativistic backward-wave oscillator leads to several beneficial effects, including (a) enhanced interaction efficiency (40%), (b) operation at very low and possibly zero guiding magnetic field, (c) tunability by controlling the plasma density, (d) high degree of spectral coherency, and (e) operation well above the vacuum limiting current.

I. INTRODUCTION

The birth of plasma microwave electronics dates back to 1949 when several authors[1,2] discussed the excitation of electromagnetic waves in a plasma through a beam–plasma instability. In their work, fast beam electrons induced the Čerenkov radiation of slow electromagnetic waves in a background plasma (plasma waves), and this mechanism was therefore described as stimulated Čerenkov radiation. A real life plasma is a complicated medium, especially when immersed in a magnetic field. If we view a plasma as a medium for the propagation of electromagnetic waves, then it is a medium that is dispersive, resonant, anisotropic, inhomogeneous, nonlinear, refractive, lossy, and unstable. Workers in the field of coherent electromagnetic radiation sources of various kinds, therefore, often try to avoid plasma in their devices.

Nevertheless, researchers in the field have also recognized the possible advantages of introducing background plasma into coherent sources of electromagnetic radiation.[3–7] For simplicity, we can consider two extreme cases, those of high and low background plasma densities.

In the first case, the background plasma density is high enough that the plasma frequency is roughly equal to the radiation frequency ($\omega_p \approx \omega_r$). In this case, it is anticipated that its presence may eliminate the need for resonators and/or spatially periodic structures commonly used in sources of coherent radiation. Under these conditions, the plasma itself can serve as an electrodynamic system in which an electron beam can excite electromagnetic waves, since the plasma has a spectrum of natural oscillations. Furthermore, since the natural frequencies of a plasma depend primarily on the plasma density, the diameter of the plasma column, and the external magnetic field, these parameters can be externally controlled and efficient production of radiation at millimeter and submillimeter wavelengths was considered possible. In addition to these benefits, high gain[5] (15 dB/cm) and possible enhanced efficiency has been predicted as a result of increased bunching due to the plasma neutralization of the beam's ac space charge. Initially only nonrelativistic electron beams were used because the beam and plasma wave synchronism can easily be satisfied under these conditions. Some of the benefits mentioned above were confirmed experimentally in the centimeter wavelength range.[5–7] When an effort was made to move into shorter wavelengths while still using nonrelativistic electron beams, the research encountered difficulties. The most serious problem was associated with coupling the electromagnetic radiation into and out of the plasma. Plasma waves which are excited by nonrelativistic beams are characterized by very slow phase velocities (quasielectrostatic) and are mostly trapped within the plasma. This limitation was especially important in dealing with amplifiers. Most important, perhaps, is the observation that the phase velocity of electromagnetic waves in a plasma excited by relativistic electron beams can be close to the speed of light and may greatly reduce the difficulty associated with coupling the radiation into and out of the plasma. Another problem is that of producing stable, low noise plasmas with densities of 10^{14} to 10^{15} cm^{-3}, as required for millimeter and submillimeter waves.

In the second case, the background plasma density is low enough that the plasma frequency is much smaller than the radiation frequency ($\omega_p \ll \omega_r$) and its presence only slightly modifies the dispersive characteristics of the external electrodynamic structure. If, in addition, the electron beam plasma frequency is on the order of the background plasma frequency ($\omega_{pb} \lesssim \omega_p$), electrostatic beam neutralization is possible. Under these conditions the plasma is expected to allow the propagation of beam currents well above the vacuum limit in microwave devices and therefore permit operation at higher radiation power levels. Early work summarized in a review paper[3] showed that plasma-loaded coherent sources of electromagnetic waves operating in this low background density regime and employing relativistic electrons can compete successfully with vacuum sources in terms of both radiation power and efficiency. Continued research aimed at increasing the radiation power in these devices has led to the development of plasma-filled BWO's.[8,9]

In this paper we shall describe a backward-wave oscil-

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lator (BWO) filled with a low-density ($\omega_p < \omega_r$) background plasma driven by a relativistic beam of electrons. This experiment showed not only the anticipated ability to propagate beam current above the vacuum limit, but also a surprising increase in the efficiency of the interaction as well as other beneficial effects. Section II summarizes the results of the linear theory of a plasma-filled corrugated-wall waveguide. In Sec. III we include a description of the results of the University of Maryland experiment along with some important observations based on these experimental results. Finally, Sec. IV discusses the conclusions and possible explanation of the observed results.

II. SUMMARY OF THE LINEAR THEORY OF A PLASMA-FILLED CORRUGATED-WALL WAVEGUIDE

In this section we shall briefly review the linear theory of plasma-loaded slow wave structures,[10–13] and show that (a) the spectrum of the low-frequency ($\omega < \omega_p$) plasma guide modes is "dense" and (b) the interaction of ballistic electron beam modes with the dense spectrum of plasma modes is unstable. Generators of coherent radiation (like BWO's) often employ retarding electromagnetic structures with spatial periodicity such as iris-loaded waveguides, coupled cavities, or helix wires instead of smooth waveguide systems. These periodic structures (also known as slow wave structures) provide for effective conversion of charged particle energy to electromagnetic radiation by matching the phase velocity of the wave to that of the particles. When filled with plasma and driven by a relativistic electron beam, some experimental devices[8,9] have produced electromagnetic radiation with considerably enhanced efficiency. We shall therefore start with the description of the dispersive characteristics for two families of waves which can be supported by an infinitely long, plasma-filled, corrugated-wall waveguide.

Figure 1(a) shows schematically a corrugated waveguide. However, most of the features to be described apply equally well to other spatially periodic structures. The structure consists of an axisymmetric, cylindrical waveguide whose wall radius, $R(z)$, varies sinusoidally according to the relation $R(z) = R_0 + h\cos(k_0 z)$ where h is the corrugation amplitude, $k_0 = 2\pi/z_0$ is the corrugation wave number, and z_0 is the corrugation period. We consider a perfectly conducting structure loaded with a uniform plasma of density N_p, immersed in a strong, longitudinal magnetic field ($B_z \to \infty$). A monoenergetic electron beam with an axial streaming velocity v_b and radius R_b is assumed to propagate along the z axis. Of interest are waves that can axially bunch a stream of relativistic electrons, and therefore only axisymmetric transverse magnetic waves will be considered.

When a periodic structure is loaded with plasma, its original dispersive characteristics are modified. The new dispersion relation was described and analyzed in separate publications[11,13] and a brief summary of the results will be given here. A plasma-loaded periodic structure can support two families of waves, the high-frequency ($\omega_r > \omega_p$) modified electromagnetic waves and the lower-frequency modified plasma waves.

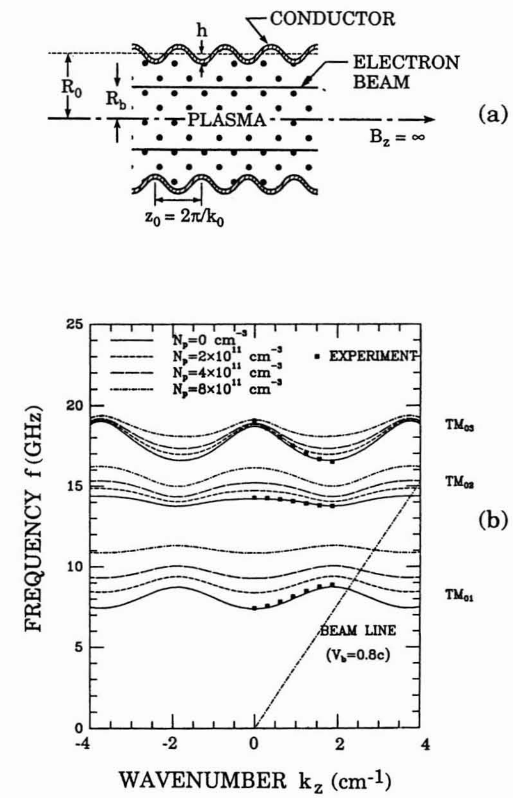

FIG. 1. A plasma-loaded spatially periodic structure. (a) Schematic diagram of a plasma-filled, corrugated-wall waveguide. (b) The dispersive characteristics of the familiar TM_{0s} family of modes as modified by a background plasma. The experimental results for a vacuum are shown as solid squares ($R_0 = 1.5$ cm, $z_0 = 1.67$ cm, $h = 0.4$ cm).

The first is the familiar, high-frequency, axisymmetric TM_{0s} family of transverse magnetic modes which are modified by the plasma. These modes are upshifted in frequency[11] in comparison with their vacuum counterpart.[14] Figure 1(b) displays the electromagnetic dispersion curves for a plasma-loaded spatially periodic system having the following dimensions: $R_0 = 1.5$ cm, $Z_0 = 1.67$ cm, $h = 0.4$ cm. The solid line is the calculated vacuum dispersion curve and the dashed lines describe the calculated dispersive characteristics of the same slow wave structure when filled with a background plasma of various densities. In a series of experiments[15] we carefully measured the dispersive characteristics of a few modes of the vacuum slow wave structure and found them to be in excellent agreement (<1%) with the calculation as can be seen from the figure. The experimental results are shown as solid squares. These modes have been shown to be unstable when driven by a relativistic electron beam,[11,12] and therefore useful for generation of coherent electromagnetic radiation.

The second is a new family of low-frequency ($0 \leqslant \omega \leqslant \omega_p$) periodic plasma guide modes[13] which we label as PPG waves. These low-frequency modes are closely related to the Trivelpiece–Gould[16] modes in smooth waveguides filled with a plasma. The spectrum of the con-

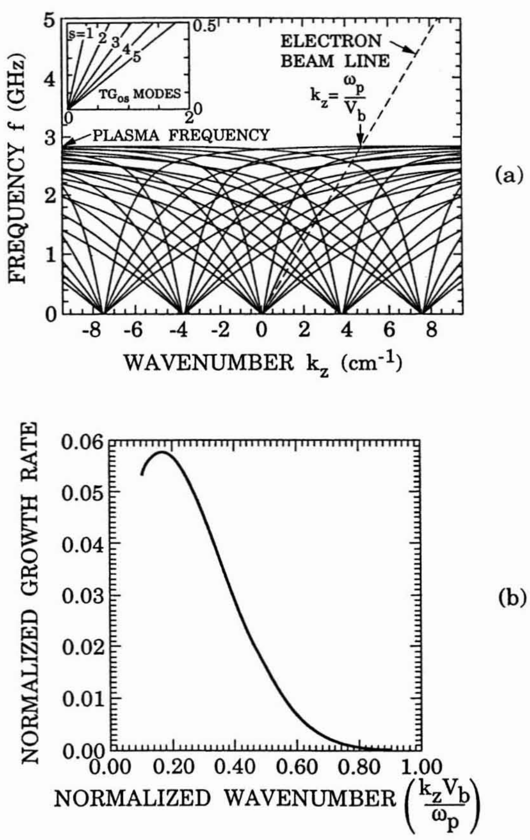

FIG. 2. Plasma modes in a spatially periodic structure and their growth rate. (a) A set of five uncoupled PPG_{0S} ($S=1,2,\ldots,5$) curves shifted by the wave number of the slow wave structure ($f_p=2.84$ GHz). Note the origin of the dense spectrum. (b) The behavior of the normalized growth rate on the wave number for an electron beam in a plasma-loaded corrugated waveguide.

ventional Trivelpiece–Gould modes in the periodic case is drastically modified by the periodicity of the structure in a way that produces a fundamentally new sort of spectral behavior, a "dense spectrum." The space-filling nature of the dense spectrum results from two fundamental features of the PPG modes: (1) all of the different radial modes (this number is infinite) are confined to a finite band of frequencies between zero and the plasma frequency, and (2) the slow wave structure adds an infinite number of additional PPG branches shifted by the spatial periodicity. Figure 2(a) illustrates a set of the five lowest-order, smooth wall, uncoupled Trivelpiece–Gould modes shifted by the wave number of the slow wave structure (k_0). The coupling of ballistic electron beam modes to the dense spectrum of plasma modes leads to an instability. The growth rate was estimated by using the Wentzel–Kramers–Brillouin (WKB) approximation and is shown in Fig. 2(b).[13]

A relativistic electron beam may interact synchronously and exchange energy with both families of waves simultaneously, leading to an increase in the power of the electromagnetic wave at the expense of the power in the plasma wave.

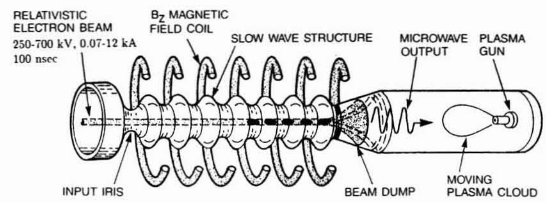

FIG. 3. Schematic diagram of the plasma-loaded BWO experiment. The electron beam is injected from the left and the radiation is extracted at the right, where the plasma is injected.

III. EXPERIMENTAL STUDIES OF A PLASMA-FILLED, RELATIVISTIC BACKWARD-WAVE OSCILLATOR

The bulk of previous experimental work in the area of plasma microwave electronics has been nonrelativistic.[5–7] The thrust of the present work is to experimentally test the validity of the beneficial effects predicted earlier (see the Introduction) in the regime of relativistic electron beams. In the experiments reported here, a hollow beam of radius ~ 0.8 cm and a radial thickness of ~ 0.1 cm is injected into a plasma-loaded corrugated-wall waveguide as shown in Fig. 3. The slow wave structure was designed to operate in the TM_{01} mode at a frequency of 8.4 GHz when driven by an electron beam accelerated to ~ 500 kV. The entire device was immersed in an axial magnetic field of 2–25 kG.

The beam was generated by a special high impedance double cathode field emission gun[17] operating over a voltage range of 300–600 kV and a beam current range of 70–200 A. Microwave signals were sampled in the device output transition section via a sidearm hole coupler and also at the output window via a horn pickup antenna. The device was filled with an externally injected background plasma, with densities adjustable over the range of 10^9 to 10^{12} cm^{-3}. The efficiency of converting the beam energy into electromagnetic radiation (defined as peak rf power/peak beam power) is plotted in Fig. 4 for our plasma-loaded (solid line) and vacuum (dashed line) BWO. The curves describe the measured maximum efficiency versus the guiding axial magnetic field strength. In this figure the plasma density was optimized at each point. The results shown in Fig. 4 display the following interesting features. First, the plasma greatly enhances the operating efficiency, from about 20% to 40%. A plasma efficiency enhancement by a factor of 2 was achieved when the electron beam current was relatively small, two or three times the start oscillation current, and the vacuum BWO efficiency is about 20%. At much higher beam currents (2 kA) when the vacuum BWO efficiency is only about 5%, the plasma-loaded BWO peak efficiency is eight times larger (40%). Second, there is a sharp resonant decrease in the operating efficiency for two values of magnetic field strength. The first resonant interaction at 7.5 kG corresponds to a cyclotron absorption at the beam's fundamental cyclotron fre-

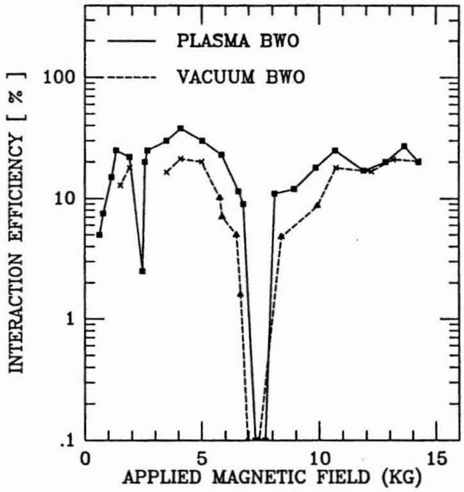

FIG. 4. The maximum efficiency of vacuum (dashed line) and plasma-loaded (solid line) BWO as a function of the axial magnetic field intensity (the plasma density was optimized at each point). The beam current is 100–200 A.

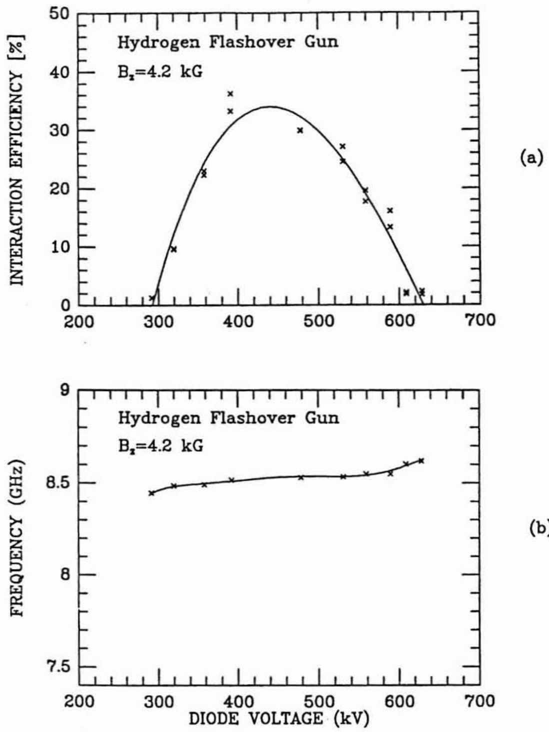

FIG. 5. The operating characteristics of a plasma-loaded BWO. (a) The dependence of the interaction efficiency on the electron beam injection energy. (b) The dependence of the microwave frequency on the electron beam injection energy (the device is locked to a single axial mode over most of the voltage range).

quency while the second (at 2.5 kG) corresponds to absorption at the third cyclotron harmonic.

Cyclotron absorption is expected to take place at a specific magnetic field intensity for which the displaced space-charge wave line $\omega=(k+k_0)v_b+\omega_{pb}$ overlaps the cyclotron wave line $\omega=kv_b+l\omega_c/\gamma$. Here, ω_c is the beam nonrelativistic cyclotron angular frequency, γ is the electron relativistic factor, l is the cyclotron harmonic number, and ω_{pb} is the relativistic beam plasma frequency. The cyclotron absorption condition is satisfied when

$$l(\omega_c/\gamma)=(2\pi/z_0)v_b-\omega_{pb}. \tag{1}$$

The magnetic field needed to satisfy the cyclotron absorption condition as calculated from Eq. (1) is in agreement with the experimentally measured values [ω_{pb} does not play an important role in Eq. (1) for the parameters of our experiment].

The third important observation based on Fig. 4 is that the device can operate efficiently even when the magnetic field is very low (0.8 kG). In fact, the decrease in the operating efficiency below 1 kG is attributed to a serious deterioration in the beam quality and eventually to the failure of the field emission gun. In fact, it has been demonstrated by another group that a plasma-loaded BWO can operate efficiently even in the absence of a guiding magnetic field if proper gun operation can be maintained.[18]

Figure 5(a) displays the dependence of the efficiency on the beam energy, reaching a maximum value of about 40% (background plasma density is kept constant). Over most of the voltage range (300–600 kV) the device is locked to a single axial mode operation (the transverse mode is TM_{01}). Most of the change in frequency occurs at the extremes of this voltage range. The total measured frequency change (130 MHz) corresponds to the calculated switched from one axial mode to the next [Fig. 5(b)]. The output frequency was accurately measured by beating the BWO output against a fixed frequency source (heterodyning). Fast Fourier transforms of the beat wave indicate that output radiation is characterized by a high spectral purity as indicated in Fig. 6. The linewidth ($\Delta\omega_r/\omega_r<3\times10^{-3}$) represents an upper limit since it includes the line broadening due to the finite duration of the radiation pulse.

The background plasma density was found by direct measurement (Langmuir probes) and verified by measuring the frequency upshift of the output radiation due to the presence of the plasma. It is not surprising that frequency tunability can be achieved by exercising control over the background plasma density. Indeed, a tunability range of 0.2 GHz was achieved as can be seen from Fig. 7. In this figure, the solid line is the calculated frequency shift and the solid squares are the measured values.

In Sec. II the spectrum of the low-frequency background plasma waves was discussed. The presence of the low-frequency (1 GHz $<f<$ 2 GHz) plasma oscillations was measured directly by an external pickup antenna and a wideband scope. In the absence of any periodic structure, the power of the plasma waves was decreased by 30 dB. The power of these plasma modes radiating out of the plasma-loaded BWO has been plotted versus the axial magnetic field intensity in Fig. 8. It shows the power leaking out of the plasma and detected by a pickup horn located about 1.5 m away from the interaction region. The actual

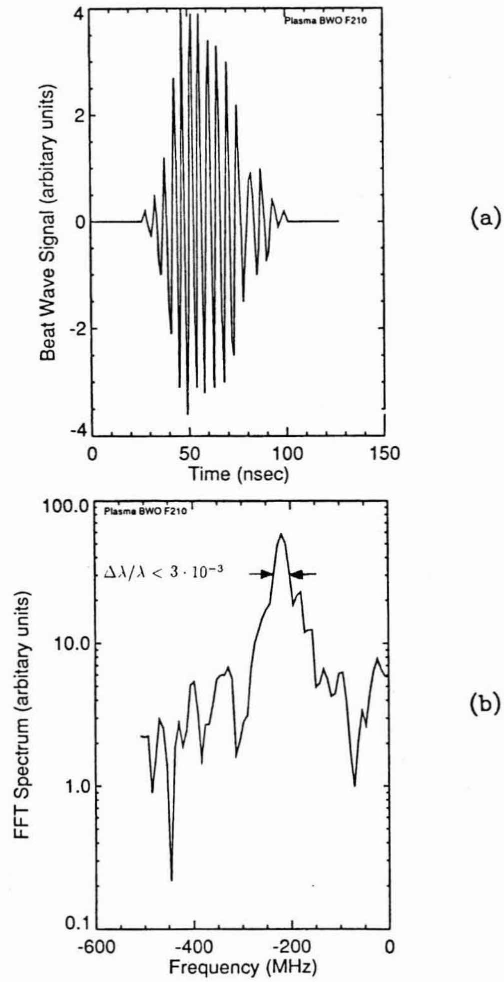

FIG. 6. The measured spectrum of the microwave radiation of a plasma-loaded BWO. (a) The beat wave signal from a heterodyne detector; (b) fast Fourier transform of the beat wave. Note the high spectral purity at FWHM (beam voltage=480 kV, beam current=150 A).

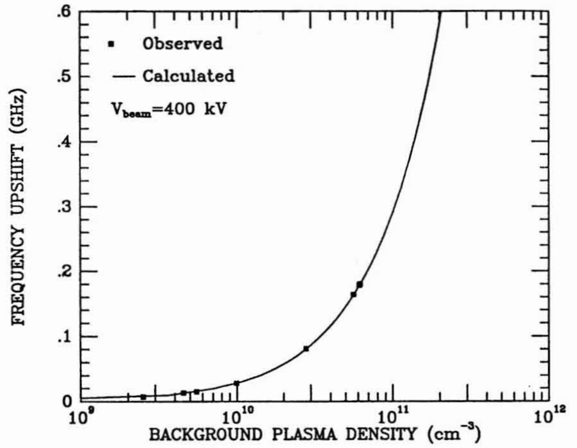

FIG. 7. The tuning range of a BWO versus the background plasma density. Tunability over 0.2 GHz was demonstrated.

plasma wave power in the interaction region is probably much higher since the plasma waves are partly trapped within the plasma. It is interesting to note the sharp increase in the emission power around 7 kG, where the beam cyclotron absorption takes place (see Fig. 4).

IV. DISCUSSION

The introduction of a low-density (3×10^9–6×10^{10} cm^{-3}) background plasma into a relativistic BWO has been shown to have quite a few beneficial effects. First, operation at very low magnetic field (800 G) has been successfully demonstrated and operation without a guiding magnetic field has been demonstrated by another group.[18] Second, enhanced efficiency (up to 40%) has been demonstrated while maintaining a high degree of spectral purity ($\Delta\omega_r/\omega_r < 3\times10^{-3}$). Third, frequency tunability over a range of 200 MHz has been demonstrated by exercising control over the background plasma density. Fourth, it has been shown that transport of large electron beam current in the presence of a background plasma is possible. In our studies, beam currents as high as three times the vacuum limit were successfully transmitted, limited only by the current handling capabilities of our field emission gun. It seems likely that even higher current is possible. Finally, it has been shown that the plasma cannot be treated as a simple dielectric medium.

A number of attempts have been made to explain the observed enhancement of efficiency in a plasma-filled BWO. The earliest[12] suggests that the dielectric properties of the plasma shift the dispersion curves of the cold structure, thus altering the operating frequency determined by the intersection in the ω-k plane of the Doppler beam line with the cold structure dispersion relation. An enhancement in the linear growth rate is predicted when the intersection occurs for zero group velocity. However, nonlinear theoretical studies of the basic BWO interaction indicate that while there may be a large enhancement in growth rate occurring at zero group velocity, the nonlinear effi-

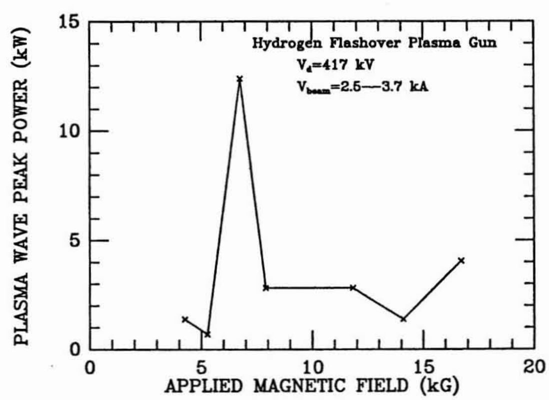

FIG. 8. Peak power of plasma radiation (below 2 GHz) versus the intensity of the guiding magnetic field. Beam voltage $\simeq$420 kV, beam current $\simeq$2.5–3.7 kA.

ciency does not show a similar enhancement. In fact, the conditions for maximum growth rate and maximum efficiency are different.

A second possible explanation of the plasma effects has been suggested by a particle in cell simulation of a BWO.[19] An enhancement was observed in the simulation when plasma was added. The interaction enhancement was associated with a change in axial wave number due to the plasma dielectric. Our studies of this subject have shown that in the absence of reflections from the boundaries of the interaction region, the efficiency of energy extraction from the beam is unaffected by small shifts in the structure's dispersion curves, such as those which would be caused by a plasma. The models discussed previously assumed no reflections at the output of the BWO.

For the structure used in the Maryland experiment the reflection coefficient at the end of the structure where the beam enters is unity and the reflection coefficient at the end where the electron beam exists is in excess of 0.7. These reflections have two effects which can be important for a plasma-filled BWO.[20] First, because of the reflections and the resulting interference between backward and forward propagating waves, the start oscillation current becomes a sensitive function of frequency. Roughly speaking, frequencies for which the interference is constructive have relatively low start currents while frequencies for which the interference is destructive have relatively higher start currents. In a vacuum BWO the operating frequency is determined primarily by the intersection in the ω-k plane of the Doppler beam line with the characteristic dispersion curve for the cold structure. Therefore, the starting current dependence on frequency translates to a dependence on beam voltage.

In the nonlinear regime the constructive and destructive interference associated with end reflections leads to a dependence of the nonlinear efficiency on frequency similar to that of the start current. In a plasma-filled BWO the dispersion curves of the structure can be modified by the dielectric of the plasma. In this way a small amount of plasma can induce a small frequency shift in the radiation. This frequency shift coupled with the interference associated with reflections from the boundary can produce variations in efficiency. For obtaining maximum efficiency enhancement, according to this mechanism, the background plasma frequency should be of the order

$$\omega_p^2 \sim \omega_r \pi / T, \tag{2}$$

where T is the electron transit time in the interaction region. Our studies[20] of these effects indicate that enhanced efficiency is indeed possible, but not as large as that observed in the experiments (40%). Thus, some other explanation is still required.

A second consequence of the reflection of the backward wave at the beam entrance tunnel, which is potentially important for plasma-loaded BWO's, is the existence of a standing wave in the interaction region.[21] The inhomogeneity in the electric field energy density associated with this standing wave gives rise to a ponderomotive force which acts on the plasma electrons. In fact, we have estimated the ponderomotive potential in the Maryland experiment to be of the order of 30 keV. This potential is likely to have a large effect on the plasma electrons, causing their density to be quite nonuniform with axial distance. The resulting modulations in the electron density of the background plasma will modify the dispersion characteristics of the structure. Further, the large pondermotive potentials indicate a likelihood that parametric decay processes may play a role in the plasma-filled BWO. One scenario in which the phase trapping limit on efficiency could be exceeded is if a spectrum of waves were present allowing for continuous extraction of the beam energy.

Finally, it has been suggested[22] that in a plasma BWO with a relativistic electron beam a synchronism of the beam with the backward electromagnetic wave and backward plasma wave (periodic plasma guide mode) is satisfied. Under these conditions the beam may exchange energy with both waves. Therefore, an increase in the power of the electromagnetic radiation at the expense of the power in the plasma wave over some range of values of plasma density and beam energy is possible. These areas are still open for investigation. Also open for further investigation are the effects of finite magnetic field, nonsymmetric modes, high plasma density (the plasma density is raised above the cutoff of the lowest-order waveguide mode), and the coupling of electromagnetic radiation into and out of the plasma.

In conclusion, it is anticipated that the presence of a background plasma will have beneficial effects in a variety of applications. Plasma- and gas-loaded free electron lasers were predicted[23,24] to have enhanced gain and achieve tunability (by changing the refractive index in the cavity) according to

$$(\lambda_r/\lambda_\omega) + (n-1) \simeq 1/2\gamma^2. \tag{3}$$

Here λ_r and λ_w are the wavelength of the radiation and the wiggler, respectively, and n is the refractive index. The presence of a plasma in gyrotrons should enable higher output power by overcoming the vacuum space-charge limit. Among the emerging plasma-assisted technologies that may result from these efforts are the stable, long pulse, repetitive plasma electron guns and the implementation of long pulse coherent microwave sources which can operate without a focusing magnetic field.[18]

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