High power plasma filled backward wave oscillators*

W. W. Destler, K. Minami, W. R. Lou,
Y. C. Carmel, V. L. Granatstein, R. A. Kehs,

Electrical Engineering Department and
Laboratory for Plasma and Fusion Energy Studies
University of Maryland, College Park, Maryland 20742

ABSTRACT

Relativistic backward wave oscillators (BWOs) have proven to be relatively efficient, high-power microwave sources in the centimeter wavelength range. Recent Soviet results have indicated that the use of a background plasma in such a device can serve to increase the space charge limiting current and allow operation of the BWO at higher injected beam current levels, with accompanying higher microwave power outputs. Studies currently being initiated at the University of Maryland include studies of BWO performance with fill plasmas produced by both electron beam ionization of a low pressure neutral gas background and by an independently controllable plasma source used to inject plasma directly into the BWO structure. Results of the first configuration will be reported and compared with theoretical expectations.

1. INTRODUCTION

Research on high-power backward wave oscillators (BWOs) driven by pulse line accelerators has been conducted primarily in the U.S. and the U.S.S.R. for about the last ten years.[1-5] These devices have operated at microwave output power levels in the range 100-1000 MW at frequencies between 5 and 15 GHz. Electronic efficiencies of several tens of percent have been reported. The relative simplicity of relativistic BWOs and their performance relative to other high power sources at these wavelengths makes them attractive for a variety of applications, including high power radar systems and directed energy systems.

Recently, researchers in the Soviet Union have reported impressive new results from plasma-filled Backward Wave Oscillator experiments. In this configuration, a fill plasma allows for operation of the device at higher net beam currents than would otherwise be possible.[6,7] In the reported experiments, a 700 keV, 1-5 kA, 30 ns electron beam was injected into a gas filled slow-wave structure. Neutralizing ions were produced by electron impact ionization (and subsequent ion-ion avalanche ionization) of the fill gas. The basic concept behind this work is that beam currents in BWOs must be kept well below the space-charge-limiting value,[8] given approximately by

$$I_\ell = \frac{17{,}000(\gamma_o^{2/3} - 1)^{3/2}}{[1 + 2\ln b/a][1 - f]} \text{ [A]} . \qquad (1)$$

Here γ_o is the relativistic mass factor for the beam electrons, b is the drift tube radius (or approximately the innermost radius of the slow-wave structure), a is the beam radius, and $f = n_i/n_e$ represents any neutralization provided by ions. Thus an ion background can raise the space-charge-limiting current and allow operation of the device at higher injected current levels than previously possible.

The experimental results of Tkach, et al.,[7] demonstrated that in this manner the injected current in a relativistic BWO could be raised from 2 kA to about 5 kA with a corresponding increase in microwave output power from 250 MW to about 700 MW. Electronic efficiency remained about the same.

At the University of Maryland, we have initiated experimental and theoretical studies of plasma-filled Backward Wave Oscillators as a natural outgrowth of previous studies of high power microwave radiation from relativistic BWOs.[9] In this paper, a dispersion relation

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for a plasma-filled Backward Wave Oscillator is derived following the methods in the Soviet literature in section 2. Analysis of these results indicates that the growth rate for microwave production is somewhat higher for the plasma-filled device than for a device operated in vacuum. Initial experimental results from a plasma-filled BWO in which the plasma was produced by beam ionization of an Argon fill gas are presented in section 3. In these studies, a four-fold increase in the output microwave power from the BWO was observed under optimum conditions. Conclusions are drawn in section 4.

2. THEORETICAL DISCUSSION

A schematic of the high-power BWO configuration used for these studies is shown in Figure 1. A high power (600-800 keV, 1-5 kA, 100 ns) relativistic electron beam is injected from a field emission diode into a periodic slow-wave structure. An applied axial magnetic field provides radial focusing for the beam electrons. The operating frequency of the BWO is given by the intersection in phase space of the empty slow-wave structure dispersion relation with a beam space-charge wave given by

$$\omega = v(k - \frac{2\pi n}{Z_o}) \tag{2}$$

where v is the axial velocity of the beam electrons, n is the spatial harmonic, and Z_o is the period of the ripples in the slow-wave structure. BWO's differ from travelling wave tubes in that the group velocity of the wave runs in the opposite direction to that of the beam electrons. A typical dispersion curve for a BWO is shown in Figure 2. The "backward" wave is usually reflected at the input end of the slow-wave structure by a waveguide beyond cutoff and the power is eventually propagated out of the system at the downstream end.

A dispersion relation for a plasma-filled Backward Wave Oscillator has been obtained following the technique of Bogdankevich, et al.[6] A beam of radius r_o propagates inside a slow-wave structure of mean radius R_o where $R(z) = R_o + h\cos(k_o z)$ and $k_o = 2\pi/Z_o$. It is assumed that $R_o^2 >> h^2$ and that the applied magnetic field is effectively infinite so that $\Omega = eB_o/m >> \omega_p, \omega_b$ where ω_p and ω_b are the plasma and beam plasma frequencies, respectively. Furthermore, only the TM_{01} mode is considered.

The wave components are given by:

$$\frac{1}{r}\frac{d}{dr} r \frac{dE_z}{dr} - x^2 \epsilon E_z = 0, \tag{3a}$$

$$E_r = -\frac{ik_z}{x^2}\frac{dE_z}{dr}, \quad B_\phi = -\frac{i\omega}{x^2 c}\frac{dE_z}{dr} \tag{3b}$$

$$\epsilon = 1 - (\frac{\omega_p}{\omega})^2 - \frac{\omega_b^2 \gamma^{-3}}{(\omega - k_z v_\parallel)^2}, \quad x^2 = k_z^2 - (\frac{\omega}{c})^2$$

Equations (3a) and (3b) are supplemented by the boundary condition that the electric field E_t tangential to the corrugated waveguide surface is zero, i.e.,

$$E_t[r = R(z)] = \frac{E_z - E_r k_o h \sin(k_o z)}{\{1 + [k_o h \sin(k_o z)]^2\}^{1/2}} = 0. \tag{4}$$

Because of the periodic nature along z of the corrugated waveguide, E_z can be expressed as

$$E_z(r,z,t) = \sum_{n=-\infty}^{\infty} E_{zn} \exp[i(k_n z - \omega t)], \tag{5}$$

where $k_n = k_z + nk_o$ and Flouquet's theorem has been used. Next, E_z in Equation (5) can be written from Equation (3a) as

$$E_z = \sum_{n=-\infty}^{\infty} A_n J_o(x_n r) \exp[i(k_n z - \omega t)], \tag{6}$$

where

$$x_n^2 = [(\frac{\omega}{c})^2 - k_n^2][1 - (\frac{\omega_p}{\omega})^2 - \frac{\omega_b^2\gamma^{-3}\alpha}{(\omega - k_n v_\parallel)^2}]$$

and

$$\alpha = \begin{cases} 1 & \text{for a solid beam} \\ 2.405 \frac{r_o\Delta}{R_o} \frac{I_o(\omega r_o/v\gamma)}{I_1(2.405)} & \text{for a hollow beam where } \Delta \text{ is the beam thickness} \end{cases}$$

Substituting Equation (6) into Equation (3b), E_r is expressed as

$$E_r = \sum_{n=-\infty}^{\infty} A_n[- \frac{ik_n x_n}{(\omega/c)^2 - k_n^2}] J_1(x_n r) \exp[i(k_n z - \omega t)]. \quad (7)$$

Expressions E_z and E_r are substituted into the boundary condition [Equation (2)] which at $r = R(z)$ results in

$$\exp[i(k_z z - \omega t)] \sum_{n=-\infty}^{\infty} A_n \exp(ink_o z)$$

$$\times \{J_o(x_n r) + \frac{ik_n x_n k_o h}{(\omega/c)^2 - k_n^2} J_1(x_n r) \sin(k_o z)\} = 0. \quad (8)$$

This equation is a dispersion relation which implicitly relates ω to k_o. The expression, however, is only of limited use in itself, beacuse it involves unknown coefficients A_n, and it is dependent on the coordinate z. So the method used by Kurilko et al.[10] is applied, viz., Equation (8) is multiplied by $\exp(- imk_o z)$ and integrated from $z = - \pi/k_o$ to $z = \pi/k_o$ to obtain a dispersion relation which does not include A_n and z. Then, one obtains finally

$$[J_o(x_{n-1}R_o) + \frac{x_{n-1}h^2}{4R_o} J_1(x_{n-1}R_o)][J_o(x_n R_o) + \frac{x_n h^2}{4R_o} J_1(x_n R_o)]$$

$$\times [J_o(x_{n+1}R_o) + \frac{x_{n+1}h^2}{4R_o} J_1(x_{n+1}R_o)] = \frac{h^2}{4} x_n J_1(x_n R_o)$$

$$\times \{J_1(x_{n-1}R_o) J_o(x_{n+1}R_o) x_{n-1}$$

$$\times [1 - \frac{k_{n-1}k_o}{(\omega/c)^2 - k_{n-1}^2}][1 + \frac{k_n k_o}{(\omega/c)^2 - k_n^2}]$$

$$+ J_o(x_{n-1}R_o) J_1(x_{n+1}R_o) x_{n+1}$$

$$\times [1 + \frac{k_{n+1}k_o}{(\omega/c)^2 - k_{n+1}^2}][1 - \frac{k_n k_o}{(\omega/c)^2 - k_n^2}]\} . \quad (9)$$

Equation (9) has been used to obtain plots of both real and imaginary ω vs. k_z for two cases. In the first, a beam-loaded vacuum BWO, predicted operating frequency is 8.5 GHz with dispersion and growth rate characteristics as shown in Figures 3 and 4. In the second, a beam-loaded plasma filled BWO, predicted operating frequency is about 10 GHz with dispersion and growth rate characteristics as shown in Figures 5 and 6. It is interesting to note that the predicted maximum growth rate for the plasma-filled BWO is about 25% higher than that predicted for the vacuum device.

3. EXPERIMENT

An initial study of high power microwave radiation from a plasma-filled Backward Wave Oscillator has been carried out by injecting a hollow, relativistic electron beam (630 keV, 3 kA, 100 ns) of radius 0.8 cm and radial thickness 0.2 cm through an anode foil into a BWO slow-wave structure filled with low pressure Argon gas (Figure 1). For the actual BWO slow-wave structure used, $R_o = 1.445$ cm, $h = 0.456$ cm, and $Z_o = 1.67$ cm. The in-vacuum anode foil changer allowed for continuous variation of the fill gas pressure in the slow-wave structure while maintaining a high diode vacuum. The applied axial magnetic field was held constant at 11.2 kilogauss for these experiments, although previous work[9] has shown that BWO microwave output is a strong function of applied axial field. Microwave power was measured using the configuration shown in Figure 7.

Microwave output power from the experiment has been measured as a function of Argon fill gas pressure, with results shown in Figure 8. Even without any changes in the diode geometry, observed microwave power rises from a value of about 100 MW for the vacuum BWO to a value over 400 MW for the case when the Argon fill gas pressure is about 10 mTorr. As the fill gas pressure is raised further, microwave output power decreases rapidly. Current injected into the BWO slow-wave structure, measured by a Rogowski coil located immediately before the slow-wave structure on the downstream side of the anode foil, changes only slightly over this range, from 2.6 kA for the vacuum device to 3.05 kA for the device with a 16 mTorr Argon fill gas pressure.

4. CONCLUSIONS

The fourfold increase in observed microwave power from the plasma-filled Backward Wave Oscillator over that observed from the same device operated in vacuum is difficult to explain without additional study. Although the injected current did rise by about 15% when the Argon fill gas was present, and while the background plasma can be expected to reduce or eliminate the space-charge depression of the electron beam energy, neither effect alone or in tandem can explain such a large increase in the radiated power. Nonlinear theoretical studies would be required to determine if the higher growth rate predicted for the plasma-filled device could result in such significant power enhancement.

Future studies, therefore, are required to fully identify the mechanism that leads to enhanced emission in plasma-filled BWO's. Studies at different beam energies and currents, different values of the applied axial magnetic field, and experiments employing different fill gases are planned to shed light on these encouraging first results. In addition, experiments are planned in which the fill gas will be replaced by a plasma from an independently controllable plasma gun in order to provide improved control over experimental parameters.

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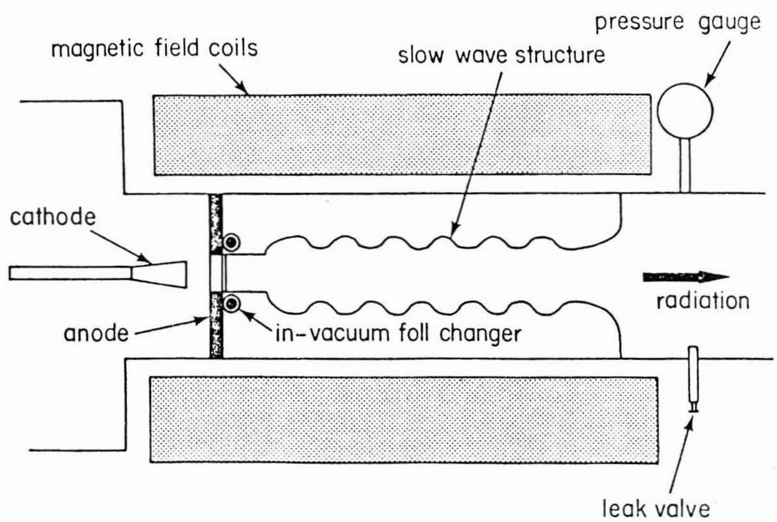

Figure 1. Backward Wave Oscillator (BWO) experimental configuration.

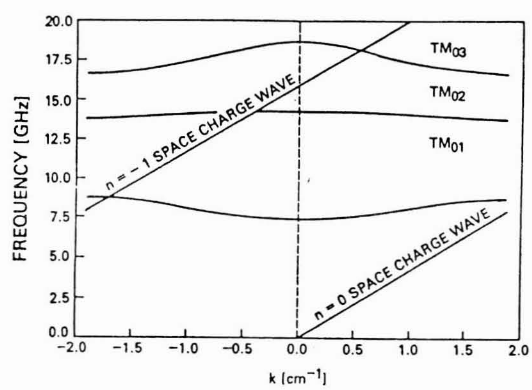

Figure 2. Empty-waveguide BWO dispersion diagram including beam line for typical experimental parameters.

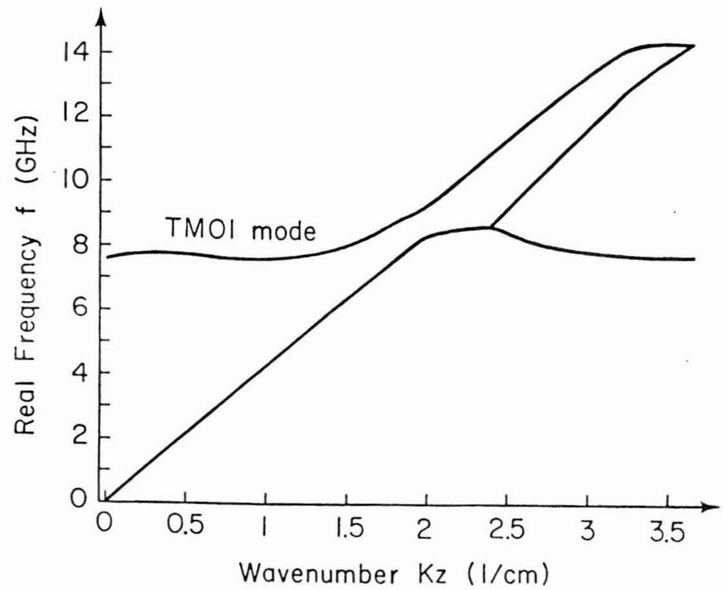

Figure 3. Beam-loaded BWO dispersion diagram for TM_{01} mode. R_o = 1.445 cm, h = 0.456 cm, Z_o = 1.67 cm, γ = 2.294, Δ = 0.2 cm, r_o = 0.8 cm, I_b = 2 kA.

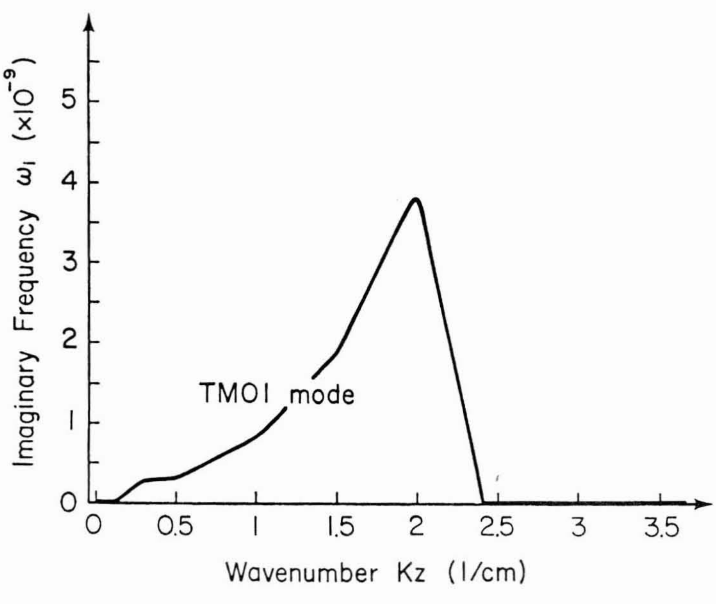

Figure 4. Growth rate vs. wavenumber for beam-loaded BWO. Parameters as in Figure 3.

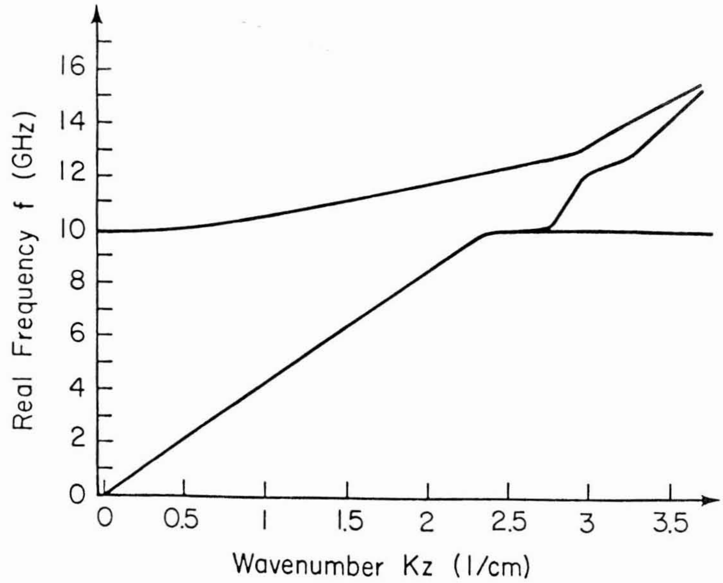

Figure 5. Beam-loaded, plasma-filled BWO dispersion diagram for TM_{01} mode with parameters as in Figure 3 and plasma density $5x10^{11}$ cm^{-3}.

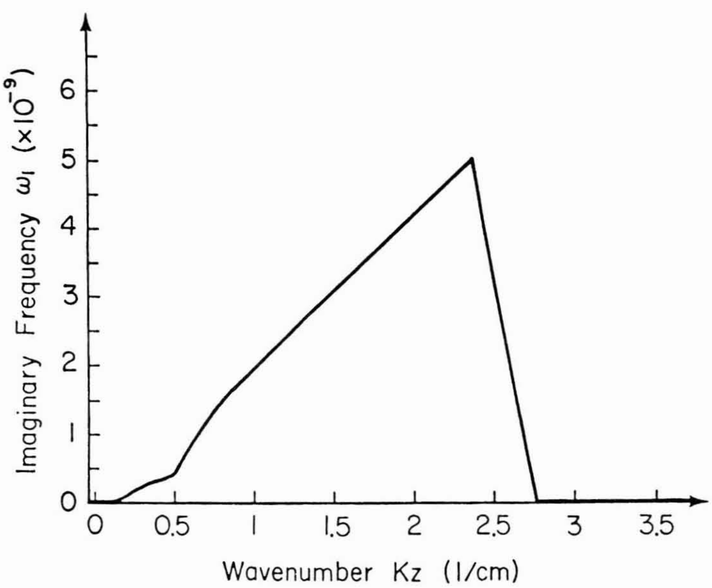

Figure 6. Growth rate vs. wavenumber for beam-loaded, plasma-filled BWO. Parameters as in Figure 5.

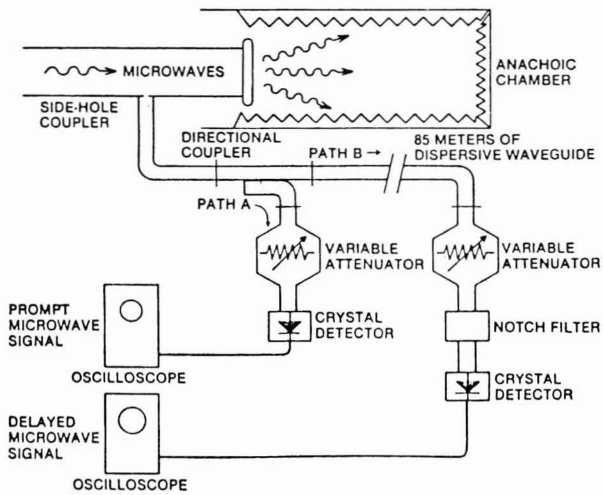

Figure 7. Diagnostic system used for microwave power measurements.

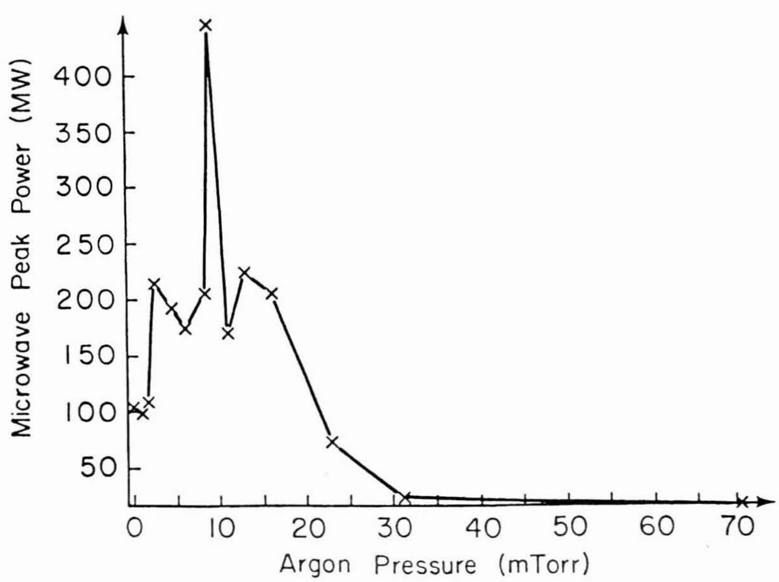

Figure 8. Microwave power from BWO vs. Argon fill gas pressure.