Observation of a resonant enhancement of microwave radiation from a gas-filled backward wave oscillator

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High-power microwave radiation at 8 GHz from a gas-filled backward wave oscillator driven by an intense relativistic electron beam has been measured. It has been observed that an order of magnitude resonant increase in microwave output power occurs at a particular pressure of the background gas. This resonance has also been observed to be strongly dependent on the value of applied axial magnetic field. Possible explanations for the observed results are discussed.

High-power backward wave oscillators (BWO's) driven by intense relativistic electron beams have proven to be relatively efficient microwave power sources in the centimeter wavelength regime. Research on relativistic BWO's has been conducted in the last decade primarily in the U.S. and the U.S.S.R. (see, for example, Refs. 1–4). These devices have typically operated at microwave output power levels of 100–1000 MW and at frequencies in the range 5–15 GHz. Electronic efficiencies up to several tens of percent have been reported. The relative simplicity of relativistic BWO's and their performance relative to other high-power sources at these wavelengths make them potentially attractive for a variety of applications including high-power radar systems and directed energy transmitting systems.

The introduction of a plasma into the slow wave structure of the BWO has been considered as a means of increasing the microwave output power and efficiency by overcoming the current limitations on the electron beam due to beam space charge effects.[5,6] The first gas-filled BWO experiment was reported by Tkach *et al.*[7,8] In this work a disk-loaded cylindrical waveguide designed for operation in the TM_{01} mode was filled with various gases at pressures less than 5 Torr. An electron beam with energy 0.8–1.0 MeV and pulse duration of 30 ns was employed. Axial magnetic fields of up to 12 kG were used to focus the beam in the BWO, and the operating frequency was about 10 GHz. The beam-produced plasma in the BWO allowed for operation at higher current levels and microwave output increased by a factor of about 2–3 over the vacuum BWO results to a peak power of 600 MW. In the present letter we describe experiments in which a resonant increase in the microwave power in gas-filled BWO's by a factor of 10 is observed under carefully controlled conditions. Possible explanations for the observed phenomena are also discussed, although much theoretical analysis remains to be performed. Related studies are also being conducted at Cornell University.[9]

Our experimental setup is shown in Fig. 1. A relativistic electron beam of 630 keV, 3 kA, and 100 ns duration[4] is produced in a field emission diode consisting of a cylindrical stainless-steel cathode of radius 0.8 cm and radial thickness 0.2 cm and a 5-μm-thick aluminized Mylar anode foil. The anode-cathode gap was 1.5 cm and the diode vacuum was maintained at 5×10^{-6} Torr. The anode foil is changed after each shot using an in-vacuum foil changer. The slow wave structure is axially symmetric and the corrugated inner radius varies as $r(\mathrm{cm}) = 1.445 + 0.456 \sin(2\pi z/D)$ over an axial length of 14.3 cm; the characteristic period of the structure is $D = 1.67$ cm. The oscillation frequency of the BWO was calculated to be 8.4 GHz.[4] The entire device is immersed in an axial magnetic field whose strength can be varied over the range 5–20 kG. The electron beam on the downstream side of the anode foil is passed through a 10-cm-long pipe 2.35 cm in diameter before entrance into the slow wave structure. This pipe acts as a waveguide beyond cutoff at the BWO operating frequency, and the reflected microwaves propagate downstream and are eventually absorbed in an anechoic chamber. A calibrated directional coupler designed for the TM_{01} mode couples a small fraction of the radiated power to the detection system. The signal is then attenuated by 99 dB of fixed attenuation before being passed to a calibrated detector and a Tektronix 7104 fast oscilloscope. The observed output frequency is approximately 8.4 GHz for the vacuum BWO as measured by standard microwave mixer techniques employing a local oscillator. Prior to firing into a gas-filled BWO, tests of the vacuum BWO were conducted to ensure that microwave output power was unaffected by the presence of the anode foil which was added to allow different ambient pressures in the diode and slow wave structure. No

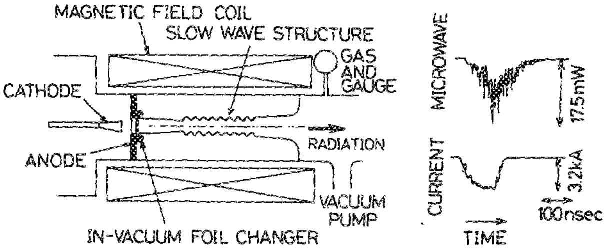

FIG. 1. Experimental configuration used for studies of gas-filled backward wave oscillator. Typical microwave output (top) and injected current (bottom) waveforms are also shown.

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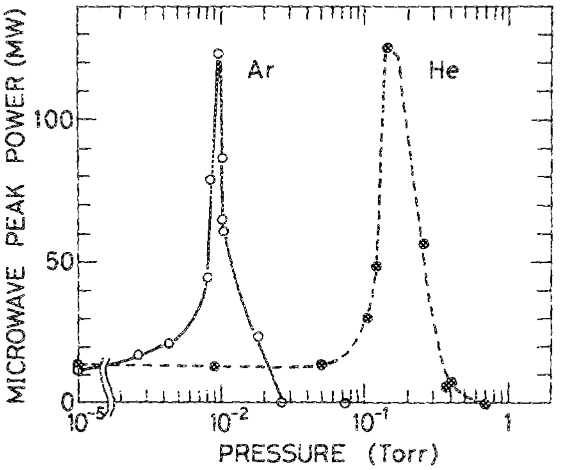

FIG. 2. Peak microwave power vs fill gas pressure for helium and argon fill gases. Axial magnetic field was 11 kG.

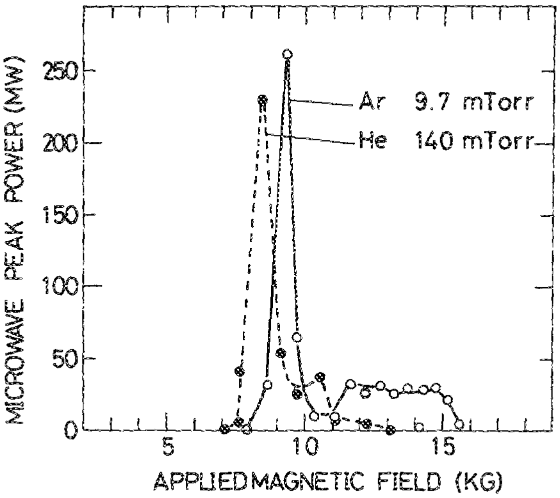

FIG. 3. Peak microwave power vs applied axial magnetic field for argon at 9.7 mTorr and helium at 140 mTorr.

significant differences were observed when the device was operated with and without the anode foil.

Typical beam current and microwave emission waveforms for the gas-filled BWO are shown in Fig. 1. The microwave pulse is roughly triangular in form and the maximum power is observed toward the end of the beam current pulse. Some microwave power is observed even after the termination of the electron beam pulse. Microwave output reproducibility from shot to shot is typically within 20%. In Fig. 2 peak microwave power versus gas fill pressure is plotted for helium and argon fill gases. Applied magnetic field was held constant at 11 kG. A strong peak in the microwave output power is observed for argon at about 9.7 mTorr and for helium at about 140 mTorr.

When the ambient pressure of the two gas species is held constant near these optimum values (within about 10%) and the magnetic field strength is varied, the results plotted in Fig. 3 were obtained. The strong peak in measured microwave power observed in each case is, however, in strong contrast to results obtained when the device is operated in vacuum.[4] It is interesting to note that the peak in microwave output power occurs at slightly different values of applied magnetic field for the two gas species. Frequency measurements indicate that in all cases the oscillation frequency was in the range 8.2–8.7 GHz, consistent with theoretical expectations.[5,10] Injected beam current rose only slightly from vacuum BWO operational values, from about 2.6 kA to about 3 kA, and no attempt has yet been made to increase the injected current by changes in the anode-cathode gap.

In attempting to understand the physical processes at work in the experiment, one must identify both the plasma production mechanism and the mechanism that leads to enhanced microwave emission at selected pressures and magnetic field strengths. The plasma production is probably not caused solely by electron-impact ionization of the background gas, since the cross sections for ionization of argon gas at these electron energies and gas pressures are simply too small to account for significant plasma production.[11,12] For the electron beams used in the experiment, $n_e = 5\times 10^{11}$ cm^{-3} and the beam space charge depression is about 60 kV. Thus the electric field strength in the slow wave structure is about 10^5 V/cm, a number comparable to the rf electric field strength in the microwave pulse inside the slow wave structure. Thus another likely cause of ionization appears to be breakdown of the fill gas due to the dc and rf electric fields in the slow wave structure.

The resonant increase in microwave power observed at specific values of fill gas pressure and applied axial magnetic field is not fully understood at this time. Following the methods used by Bogdankevich *et al.*[5], we have solved for a dispersion relation for an infinitely long plasma-filled backward wave oscillator. For a background plasma density of 5×10^{11} cm^{-3}, the predicted growth rate for the beam-wave interaction is about 25% higher than for the vacuum case.[10] Nonlinear calculations would be required to determine if a higher growth rate would actually lead to higher microwave output power, but in any event, these calculations do not appear to indicate that the growth rate should be such a strong function of plasma density or applied magnetic field as observed in our experiments.

On the other hand, Kirilko *et al.*[6] have predicted that a resonant increase in growth rate would occur when the frequency of background plasma oscillations was equal to the frequency of the electromagnetic wave excited by the beam in the periodic structure. They also predicted that the resonance would be especially strong if this synergism occurred near a limiting frequency of the electromagnetic wave dispersion curve so that both forward and backward waves would be excited in the periodic structure, and feedback in the device would be more effective. In fact, the BWO in the present experiment was designed to operate near the upper limiting frequency.[4] Thus we estimate that resonance occurs when the background plasma oscillation frequency $f_p = c/2D$, assuming that the beam electrons are streaming near the speed of light (i.e., $v_z \approx c$). Taking $f_p = [(n_p e^2/m\epsilon_0)^{1/2}]/2\pi$, where n_p is the background plasma density, we find that at resonance $n_p \approx \pi/(4r_0 D^2) \approx 10^{12}$ cm^{-3} ($r_0 = e^2/4\pi\epsilon_0 mc^2$ is the classical electron radius). This level of background plasma density could readily have been created by passage of the electron beam through the background gas at a specific value of gas pressure.

Another factor that may relate to the enhanced emission at specific background gas pressures is the improved propagation environment for the electron beam that the background plasma provides. Studies of the propagation of intense beams through plasma backgrounds in the presence of strong applied magnetic fields have indicated that effective propagation occurs only in narrow pressure ranges.[13] Thus the background fill gas may improve the overall beam quality and lead to more effective beam-wave interactions.

The fact that a strong enhancement of microwave emission occurs only for a narrow range of applied axial magnetic fields is indicative of the fact that cyclotron resonance effects may also play an important role in the experiment.[14] Tkach *et al.*[8] observed that under certain conditions enhanced microwave emission could be obtained when the Cherenkov and cyclotron resonances were at nearly the same frequency. For the experimental conditions under which these results were obtained, the calculated cyclotron frequency is approximately 10 GHz, a value reasonably close to the measured oscillation frequency of 8.2–8.7 GHz. Finally, we note that higher frequency radiation involving cyclotron harmonics has been observed at reduced power levels in the vacuum BWO,[15] but this portion of the frequency spectrum has not yet been studied in the gas-filled device.

In conclusion, resonant emission of enhanced high-power microwaves from a gas-filled backward wave oscillator has been observed. Emission has been shown to be a strong function of both fill gas pressure and applied axial magnetic field. Theoretical studies to positively identify the radiation mechanism are currently under way.

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