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Study of a plasma-filled X-band backward wave oscillator

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We present experimental studies of a plasma-filled X-band backward wave oscillator (BWO). Depending on the background gas pressure, microwave frequency upshifts of up to 1 GHz appeared along with an enhancement of a factor of 7 in the total microwave power emission. The bandwidth of the microwave emission increased from $\leq$0.5 to 2 GHz when the BWO was working at the rf power enhancement pressure region. The rf power enhancement appeared over a much wider pressure range in a high beam current case (10–100 mT for 3 kA) as compared to a lower beam case (80–115 mT for 1.6 kA). The plasma-filled BWO has higher power output compared to the vacuum BWO over a broader region of magnetic guide field strength.

Vacuum slow wave devices have been attractive high-power microwave sources since the early 70s. Introduction of plasma into a vacuum microwave device can have several beneficial effects. Background plasma can neutralize beam charge, allowing beam propagation in the slow wave device well above the space-charge limited current, yielding higher power microwave output. Plasma can also enhance the interaction efficiency, by allowing greater bunching through neutralization of space-charge effects. The first plasma-filled backward wave oscillator (BWO) demonstrated a factor of 3 in microwave power enhancement over it's vacuum counterpart.[1] Recent experiments[2] have achieved a factor of 8. These plasma-filled BWO experiments concentrated on producing high-power microwaves. In a recent theoretical description of the plasma-filled BWO[3] it was shown that the addition of plasma results in a frequency upshift in the output of the BWO, the amount of shift depending on the plasma density, n_p. An upshift up to 2.5 GHz was predicted for a plasma density of 8×10^{11} cm^{-3} for the BWO geometry considered. However, the calculation gave no information about how bandwidth changes with plasma density. High-power, frequency tunable and high-power, broadband microwave devices have some useful applications. The goal of this work was to study the effect background plasma had on the microwave frequency and bandwidth of the output radiation in a high-power plasma filled BWO.

Our experimental setup (Fig. 1) uses a hollow electron beam (650 kV, 1.5–3 kA, 500 ns pulse duration) with 1.8 cm outer diameter, and 0.2 cm thickness, produced by field emission from a graphite cathode. Beam current and voltage were monitored near the cathode, with down stream current measured by a shunt resistor. Plasma was produced by electron beam impact ionization of background neutral helium gas which filled the BWO and the diode. To measure the plasma density, we used a 9.6 GHz X-band magnetron as the rf source. In order to avoid strong X-band TM$_{01}$ radiation and to not modify the oscillator, we replaced our BWO with a stainless-steel tube of 10 mm radius, keeping anode and cathode geometry the same. Since the X-band radiation consistently arrived 140 ns ($\pm$10 ns) into the beam pulse, we could correlate the microwave signal with the plasma density measurement at the turn on of the microwaves. The magnetron rf was fed through the plasma by X-band waveguide, carrying information about $n_p(t)$ in its phase change $\Delta\phi(t)$. The probe rf was then mixed with rf from a local oscillator so that a mixed frequency of $\sim$100 MHz was obtained. $\Delta\phi(t)$ occurs in the frequency difference $f_M(t) = f_{\text{magnetron}} - f_{\text{oscillator}}$ as a frequency change $\Delta f_M(t)$. $\Delta\phi(t)$ can be obtained by comparing this new frequency to the upshifted mixed frequency $f_{M0} = f_M(t<t_0, t_0$ is the beam start time), so that $\Delta f_M(t) = f_M(t) - f_{M0}$. With no neutral gas in the system we detected no shift in the frequency difference Δf_{M0}, for up to 3 μs. The beam voltage pulse was synchronized with the stable portion of the mixed frequency.

The BWO is a cylindrical waveguide with a periodically varying wall radius, $R(z)$, sinusoidally rippled about the mean radius, R_0, such that

$$R(z) = R_0 + h\cos(k_0 z) \text{ and } k_0 = 2\pi/z_0,$$

where $h=0.45$ cm is the ripple amplitude, $z_0=1.67$ cm is the period, and $R_0=1.45$ cm. This is a copy of the system described in Ref. 3. The BWO was immersed in a 6–18 kG guiding magnetic field. An X-band horn placed 2 meters from the end of the drift tube received the microwave emission from the BWO. The microwaves were guided through 20 meters of X-band waveguide into a screen room. Here the microwaves were measured by a crystal detector and an

1. Anode   2. Cathode
3. Reflector   4. BWO
5. Shunt resistor   6. Beam dump
7. Helium inlet   8. Magnetic coils
9. rf receiving horn   10. Attenuator
11. 8 channel X-band rf spectrometer
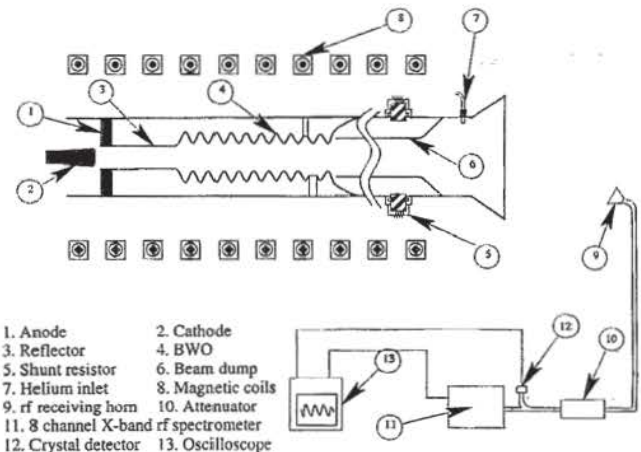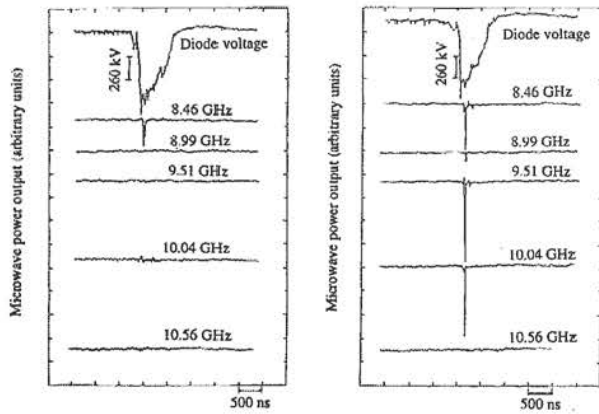12. Crystal detector   13. Oscilloscope

FIG. 1. Experimental setup.

FIG. 2. Oscilloscope traces from the microwave spectrometer and the beam voltage: (a) vacuum BWO, (b) plasma-filled BWO (60 mTorr, $I=3$ kA). The center frequency of each channel is indicated.
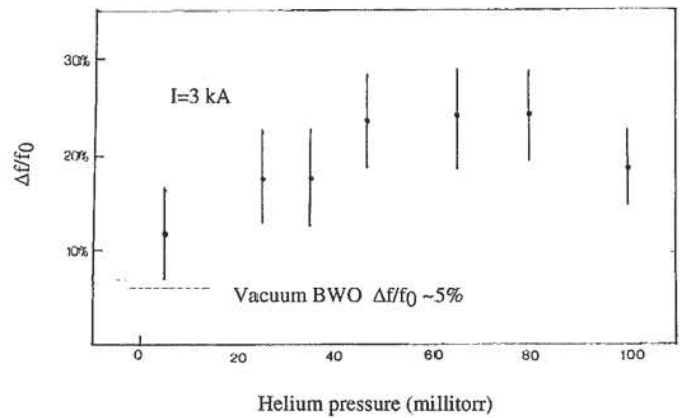

FIG. 3. Bandwidth of the microwave pulses vs background helium pressure. Δf is the frequency range of microwave output, f_0 is the vacuum rf center frequency.

X-band 8 channel microwave spectrometer, covering 8.2 GHz $< f <$ 12.4 GHz. Each channel had a bandwidth of approximately 0.5 GHz. The spectrometer filters had 50 dB stop-band insertion loss with 0.9 dB passband insertion loss.

Figure 2 (a) shows the beam voltage and the 8 channel X-band microwave spectrometer signals from the vacuum BWO for 3 kA beam current. Microwave output was always in the first channel of the spectrometer (8.2 to 8.725 GHz, 8.46 GHz center frequency). Maximum power emission was about 80 to 100 MW with microwave pulse duration of 50 ns (FWHM). This is a very short pulse, considering our beam pulse was 500 ns. However, when the BWO operated at lower level powers, the microwave emission lasted longer. For example, microwave radiation with power output 30–40 MW lasted between 130 to 150 ns. As the background neutral helium gas pressure increased in the BWO, we observed both a microwave frequency up-shift and a bandwidth increase. At low gas pressure (under 10 mTorr) and beam current of 3 kA only channel 1 and 2 of the spectrometer detected microwave signal. However, in the pressure region where the enhancement in rf power was observed (between 50 to 80 mTorr), signals appeared in the first four channels of the spectrometer. It is interesting to note that the signal in channel 1 was never less than the vacuum BWO output level, and actually its output was the largest among all channels when the background helium pressure was below 25 mTorr. When the helium pressure was between 25 and 50 mTorr, rf signals appeared in the first three channels of the spectrometer, and the signal amplitude in the second and third channel increased to the same level as the first channel. At the pressure where maximum power was obtained, the third channel detected the largest signal. This indicted a frequency upshift of 1 GHz. Figure 2(b) shows a shot taken at 60 mTorr with 3 kA beam current. If we sum the signal output from all channels of the spectrometer in Fig. 2(b) and compare to the signal in Fig. 2(a), it is more than 7 times larger. Comparison also indicated the bandwidth of the microwave emission increased from $\leqslant$0.5 GHz in vacuum to 2 GHz. We observed similar frequency upshift and bandwidth in-

crease for the 1.6 kA beam case as well. Microwave emission bandwidth as a function of the background helium pressure is shown in Fig. 3. The percentage bandwidth $\Delta f/f_0$ changed from $\leqslant$5% in vacuum to 25% at the pressure which gave maximum power enhancement.

When 3 kA of beam current was injected into the helium filled BWO, we observed a microwave power enhancement for helium pressure between 10 to 100 mTorr. The maximum microwave power emission appeared at 60 mTorr. When the beam current was reduced to 1.6 kA, the microwave power enhancement began at $\sim$80 mTorr, peaked at 110 mTorr, and then declined. The plasma filled BWO microwave power output data is shown in Fig. 4. The output is the summation of all the signals from channel 1 to channel 4 of the spectrometer (frequency range from 8.2 to 10.8 GHz) while the vacuum BWO microwave power output (indicted by the dashed line) was the signal
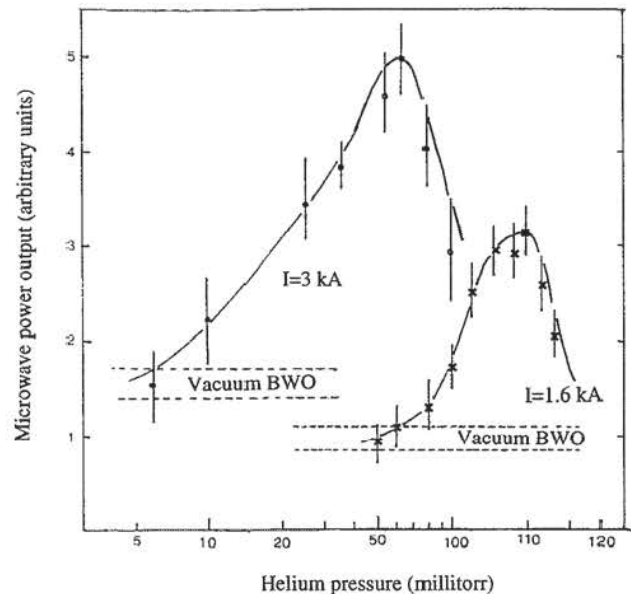

FIG. 4. Microwave power output vs background helium pressure for beam currents of 3 and 1.6 kA. Microwave output for the vacuum BWO is given by the dashed lines.

from the first channel (frequency from 8.2 to 8.7 GHz). Microwave power enhancement in a plasma-filled BWO has been reported by others.[1,2] Possible reasons for the dependence of the microwave output on the background plasma density have been discussed in Refs. 4 and 5.

Microwave power depended on the guiding magnetic field both in the vacuum and plasma-filled BWOs. In the plasma-filled BWO, we kept the background helium pressure in the maximum rf output range e.g., at ~60 mTorr for the 3 kA beam current. Microwave power peaked around 13.5 kG, with a wider range compared to the vacuum BWO. The vacuum BWO peaked at a slightly larger B field ~14.5 kG. Our 13.5 kG field is much higher than the peak rf emission field (9–10 kG) reported in Ref. 2 in their helium gas filled BWO. We are not sure of the reason for this difference.

In conclusion, our plasma-filled BWO generated between 560–700 MW (frequency between 8.2 to 10.8 GHz) microwave power in plasma and 80–100 MW (frequency from 8.2 to 8.725 GHz) in vacuum. The rf power enhancement appeared over a much wider pressure range for high beam currents than for the lower beam current driven BWO. Microwave frequency upshifted 1 GHz at the microwave power enhancement background helium pressure region for both 1.6 and 3 kA of beam current. This is less than the theory of Ref. 3, which predicts a 2.5 GHz upshift

at $n_p = 8 \times 10^{11}$ cm^{-3}. [Our plasma density measurements indicate $n_p \cong (8 \pm 1.5) \times 10^{11}$ cm^{-3}.] The background plasma will increase the beam electron kinetic energy by reducing the space-charge potential produced by the beam in the BWO. This will shift the beam wave intersection point up in frequency. However, a simple calculation shows that for our electron beam parameters, a frequency upshift of less than 200 MHz is expected. Along with the frequency upshift, bandwidth increased with plasma density. Although the rf pulse duration decreased from 50 ns in vacuum to about 20–30 ns in plasma-filled BWO this is not sufficient to account for the observed bandwidth increase.

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