Demonstration of Efficiency Enhancement in a High-Power Backward-Wave Oscillator by Plasma Injection

Y. Carmel, K. Minami,[a] R. A. Kehs,[b] W. W. Destler, V. L. Granatstein, D. Abe, and W. L. Lou
Laboratory for Plasma Research, University of Maryland, College Park, Maryland 20742
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An experimental demonstration of a strong enhancement of the interaction efficiency in a high-power relativistic backward-wave oscillator when plasma is injected is presented. Controlled plasma injection enhances the interaction efficiency over the vacuum case by a factor of up to 8 to a value of about 40%. The enhanced interaction is attributed to induced scattering of the electromagnetic radiation of electrons in an electrostatic field produced by the background plasma and a beam space-charge wave in the corrugated interaction region.

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Many varieties of high-power microwave (HPM) devices have been studied in recent years, including the well-known magnetron and klystron as well as newer devices such as the gyrotron, free-electron laser, and virtual cathode oscillator.[1] All of these sources have one thing in common—they are driven by an intense, monoenergetic, unneutralized electron beam which unstably interacts in high vacuum with an electromagnetic wave, leading to the conversion of the beam's kinetic energy into electromagnetic radiation. The power levels available from such devices have grown by an order of magnitude every decade since 1940, reaching about 10^{10} W at a wavelength of 3 cm and 10^8 W at 3 mm.[2]

This work demonstrates for the first time a strong efficiency enhancement in a relativistic backward-wave oscillator (BWO) by external plasma injection. Plasma effects in conventional microwave devices can usually be neglected since the plasma frequency of the background gas is much smaller than the plasma frequency of the electron beam ($\omega_p/\omega_{pb} < 10^{-2}$). Recent theoretical studies,[3] however, have predicted that the presence of a plasma in HPM devices may lead to greatly enhanced performance, attracting renewed scientific interest.[4] The presence of a background plasma can serve to increase the space-charge limiting current by a factor of $[1-f]^{-1}$, where $f=n_i/n_e$ represents any neutralization provided by the ions in the background plasma. The space-charge limiting current in the presence of the plasma for a thin hollow beam with a mean radius a and a thickness $\Delta \ll a$ is given by

$$I_l = \frac{17[\gamma_0^{2/3}-1]^{3/2}}{[2\ln(b/a)][1-f]} \text{ kA}. \tag{1}$$

Here γ_0 is the relativistic mass factor for the beam electrons, and b is the radius of the drift tube. By increasing the beam current through introduction of a background plasma, a new limitation is encountered which is imposed by the onset of beam-plasma instability. This instability will occur at current levels which are larger than the vacuum limiting current by the factor[3]

$$\gamma[(1-\gamma^{-2})/(1-\gamma^{-2/3})]^{3/2}. \tag{2}$$

In the case of mildly relativistic electron beams having $\gamma=3$, the actual current carried by the beam in the presence of plasma may be 7 times larger than the vacuum case. The increased injected current level simply allows operation at higher beam power and associated higher microwave power output without affecting the interaction efficiency or the physical interaction mechanism.

The plasma presence in the device can, however, also completely alter the nature of the interaction mechanism, leading to greatly enhanced device efficiency. The studies reported here are the first which clearly belong to this latter category.

Since BWO's[5] are simple devices, provide fairly effective conversion of electron beam energy into radiation, and can easily be filled with plasma, they are ideal candidates for the evaluation of plasma effects. Initial studies[6,7] utilized background plasmas produced by electron-beam-impact ionization of a low-pressure neutral-gas background, and demonstrated enhanced microwave output powers. Interpretation of the results, however, and identification of the physical mechanisms involved have proven difficult. In some of these earlier studies,[6] the increased output power was attributed to a substantial increase in injected beam current allowed by the increase in the space-charge limit allowed by the plasma. In another,[7] beam current was again increased over the vacuum BWO studies, and identification of the mechanism was complicated by the strong resonant dependence of microwave output on the externally applied magnetic field. In the work presented here, injected beam parameters were carefully held constant for both vacuum and plasma-filled BWO experiments. The resulting enhancement in BWO microwave output power when plasma is present is therefore clearly a result of an improvement in the electronic efficiency of the device. Thus this work unambiguously demonstrates efficiency

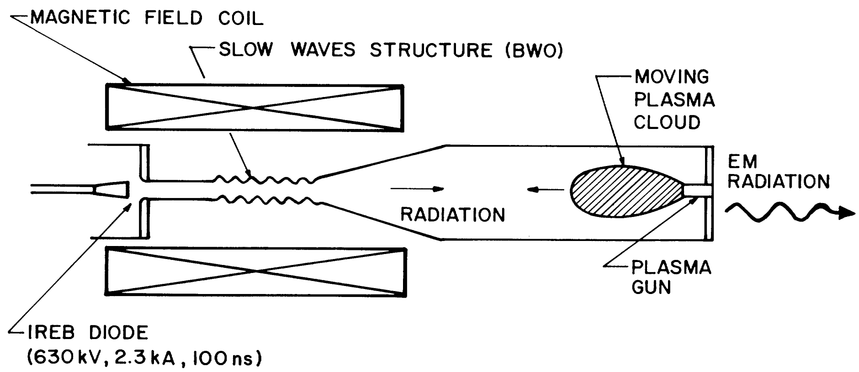

FIG. 1. Schematic diagram of a relativistic backward-wave oscillator with external plasma injection.

enhancement in a high-power microwave tube.

In the experiments, an independently controllable argon plasma source was used to externally inject plasma directly into the BWO structure as shown in Fig. 1. A hollow, relativistic electron beam (630 kV, 2.3 kA, 100 ns) of average radius 0.8 cm and electron density of about 5×10^{11} cm^{-3} was injected into a BWO corrugated-wall slow-wave structure immersed in a uniform axial magnetic field of about 12 kG. A coaxial plasma gun,[8] located about 100 cm downstream in a field-free region, generated an argon plasmoid which crossed magnetic field lines at an average velocity of about 1.2 cm/μs on its way towards the interaction region. The entire system was evacuated to pressure $<4\times10^{-5}$ Torr. The plasma column parameters were measured with 35- and 70-GHz microwave interferometers (for density) and Langmuir probes (for velocity, density, and temperature). Initial results indicate that the average plasma density could be varied continuously by changing the gun voltage and gas pressure from zero up to a maximum value estimated at $\sim10^{13}$ cm^{-3}, which is well above the corresponding beam density (5×10^{11} cm^{-3}).

Efficiency enhancement was observed over a wide range of injected plasma densities, $0<n<n_{cr}$, where n_{cr} is a critical plasma density. This critical plasma density, to be discussed later, occurred at $T\cong90$ μs on the plasma pulse time scale. The efficiency enhancement factor over vacuum BWO operation was found to be density dependent, and reached a maximum value of 8 when the electron beam was injected into an optimized plasma density. This occurs twice on the plasma pulse time scale, once during density rise ($T\cong60$ μs) and then again during density decay ($T\cong100$ μs); see Fig. 2. At these points the interaction efficiency increased to almost 40% compared with about 5% for the vacuum BWO under the same operating conditions.

From basic considerations it is possible to estimate the critical plasma density which will overdrive the device and quench the interaction. Figure 3 depicts the approximate dispersion relation of the lowest-order symmetric electromagnetic branches[9] (labeled TM_{01} and TM_{02}) as well as the plasma branches (labeled plasma waves) which we shall refer to later. Note that the intersection point of the TM_{01} mode and the electron-beam space-charge wave lies on a portion of the electromagnetic-wave dispersion relation having negative group velocity,

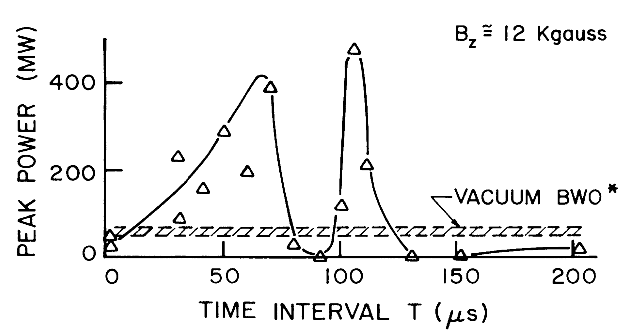

FIG. 2. Peak power output at 8.4 GHz vs the time interval between the plasma gun operation and the electron beam firing.

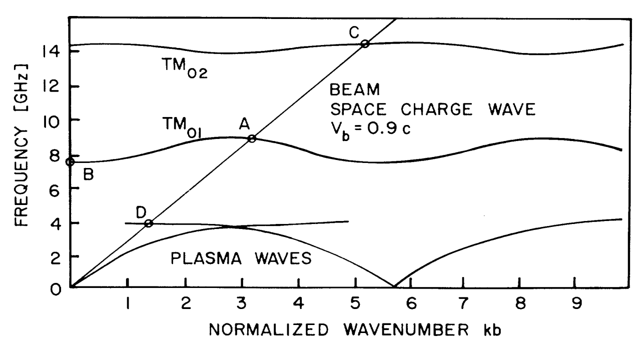

FIG. 3. The dispersion relation of plasma-filled corrugated waveguide including the electromagnetic and plasma branches, with superimposed ideal beam wave added. V_b is the beam velocity, c is the speed of light, and $b=1.445$ cm is the average radius of the corrugated waveguide, with radius given by $r=b+0.445\sin(2\pi z/1.67)$ cm.

which implies a backward-propagating wave. The backward-propagating wave is reflected by a waveguide beyond cutoff at the injection point and then detected downstream from the structure (Fig. 1). This intersection occurs close to the upper cutoff frequency of the TM_{01} passband at 8.4 GHz (point A in Fig. 3). To first order, the presence of a magnetized plasma in the slow-wave structure will raise its lower cutoff frequency above the vacuum value of 7.5 GHz (point B). If the device is overdriven to the point where the lower cutoff frequency in the presence of plasma is equal to or greater than the upper cutoff frequency in the absence of plasma, no backward-wave interaction is possible.

An approximate expression for the cutoff frequency (TM modes) of a waveguide filled with magnetized plasma is[10,11]

$$f_{co}=\frac{c}{2\pi}\left[\left(\frac{P_{nl}}{b}\right)^2+\left(\frac{\omega_p}{c}\right)^2\right]^{1/2}. \tag{3}$$

In Eq. (3) ω_p is the background plasma frequency, c is the speed of light, P_{nl} are the roots of the Bessel functions corresponding to the mode of interest, and b is the waveguide radius. When solved for the critical background plasma density which would quench the interaction, using our experimental parameters, Eq. (3) yields

$$n_{cr}=2\times 10^{11}\ \text{cm}^{-3}. \tag{4}$$

When the backward-wave oscillator was overdriven with plasma above the critical density, the fundamental TM_{01} mode at 8.4 GHz was quenched and strong, higher-frequency emission (12–18 GHz) was observed, possibly indicating mode switching from TM_{01} to TM_{02} (point C in Fig. 3).

The dramatic mode switching is shown in Fig. 4. It shows the amplitude (vertical scale) of different frequency (horizontal scale) components of the backward-wave oscillator using the dispersive line technique (different frequencies are resolved by their different propagation velocities in a dispersive waveguide). Figure 4(a) represents the spectrum emitted by the backward-wave oscillator under the condition of strong plasma enhancement, where the dominant frequency component is near 8.4 GHz. An undispersed, prompt microwave output signal is superimposed on the dispersed signal as a timing reference. Figure 4(b) represents the spectrum for an overdriven device, in which case mode switching occurred and frequency components in the range 10–18 GHz are present (TM_{02} or other high-order modes as well as plasma oscillation). At even larger plasma densities, microwave breakdown within the device will occur.

Strong microwave emission was also detected in the 18–26-GHz band, proportional in amplitude to the fundamental TM_{01} backward-wave oscillations. These high frequencies are believed to be produced by a free-electron laser interaction driven by an electromagnetic pump, as reported previously.[12,13]

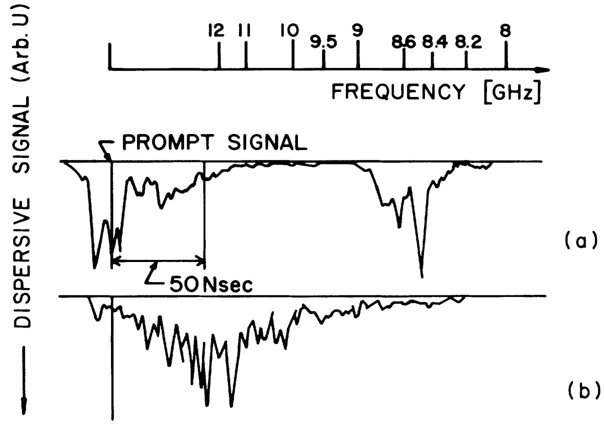

FIG. 4. Spectral results from plasma-enhanced backward-wave oscillator. (a) Maximum enhancement and (b) overdriven device.

As these experiments demonstrate, the controlled presence of a plasma in the corrugated structure strongly enhances the interaction efficiency over a very wide range of plasma densities. To understand the physical mechanism responsible for the enhanced interaction, Fig. 3 also depicts the approximate dispersion relation of a plasma-filled corrugated waveguide. It consists not only of the known slow electromagnetic branches, but the plasma branches as well (labeled plasma waves in Fig. 3). These low-frequency modes are purely plasma waves and vanish in the limit of small background plasma density ($\omega_p \to 0$). They are the corrugated-waveguide version of the Trivelpiece-Gould (TG) modes.[11] Normally, those plasma oscillations are trapped in the plasma and cannot be coupled out efficiently in the form of electromagnetic radiation. However, for the range of values of the plasma density and beam energy relevant to our work, the beam is simultaneously in synchronism (and therefore can exchange energy) with the backward branch of electromagnetic wave (point A) and the backward branch of the plasma wave (point D in Fig. 3). Under these conditions, all three waves involved have the same phase velocity, ω/k, and a strong component of axial electric field, E_z. Therefore, a strong enhancement is expected. It is believed that the greatly enhanced efficiency observed results from this mechanism, namely, induced scattering of the electromagnetic radiation of electrons in an electrostatic field produced by the background plasma in the presence of the corrugated wall.

The introduction of plasma into the device did not affect the diode voltage or current, and the beam current actually entering the slow-wave structure was unaffected by the plasma. No diode shorting due to the injected plasma was observed, and the performance of the plasma BWO with respect to variations in the applied axial magnetic field was similar to the vacuum BWO.[14] No sharp resonance (similar to the one in Ref. 7) is expected for this mechanism, and none was observed.

An efficient interaction also implies a very broad gain curve with respect to the electron beam energy. This is expected for the present mechanism since the electrons tend to stay in synchronism with both backward branches (points A and D in Fig. 3) even as the beam is losing energy. Although the effect of the plasma on beam transport inside the slow-wave structure could not be directly measured, no evidence of significant beam current striking the structure walls was observed.

It is anticipated that plasma injection may also prove beneficial in other high-power microwave devices such as free-electron laser and gyrotrons, providing frequency tunability,[15] overcoming space-charge limitations,[16] and enhancing interaction efficiencies.[17]

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[a]Permanent address: Department of Electrical Engineering, Niigata University, Niigata, Japan.

[b]Permanent address: Harry Diamond Laboratory, Adelphi, MD 20783.

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