Operation of a Relativistic Backward-Wave Oscillator Filled with a Preionized High-Density Radially Inhomogeneous Plasma

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***Abstract*— A modified relativistic (500 kV, 500 A) backward-wave oscillator (BWO) filled with a radially nonuniform preionized plasma of high-peak density (peak plasma frequency $>$ operating frequency) is studied experimentally. The effects of high plasma density in the interaction region as well as the relativistic diode and the output horn regions were studied. By protecting both the diode and output regions against plasma penetration, the plasma effects on the BWO was studied up to a peak plasma density of 8 $\cdot$ 10^{12} cm^{-3}. It was demonstrated that filling the BWO structure with high density radially nonuniform plasma leads to the following.**

1) **Suppression of high-order modes. This is a promising approach for implementing single mode operation of high-power large-diameter overmoded devices.**
2) **Frequency upshift of up to 30% (from 8.5 to 11 GHz). This demonstrates the possibility of electronic frequency tunability by controlling the plasma density.**
3) **Substantial increase in the measured microwave output power for $n_p > 10^{12}$ cm^{-3} over the corresponding vacuum value.**

I. Introduction

HIGH-power microwave oscillators driven by intense relativistic electron beams are capable of generating peak powers of hundreds of megawatts and gigawatts. Generally, these oscillators consists of some kind of an evacuated resonator into which a relativistic electron beam is injected. The resonant interaction between the beam and the appropriate modes of the resonator leads to the generation of high-power radiation.

A class of oscillators uses a corrugated waveguide as a resonator in which a linear relativistic electron beam interacts with the longitudinal component of the electric field of a mode of the corrugated cavity. The simplest and most well-studied oscillator which uses a corrugated cavity is known as a backward-wave oscillator (BWO). Relativistic BWO's are characterized by relatively good efficiency of converting beam power into coherent microwave power.

The maximum attainable microwave output power of relativistic BWO's, however, is limited by the amount of beam current that can propagate through the cavity. This is normally restricted to only a small fraction of the corresponding vacuum limiting current (I_v). Additional limitations are the small degree of frequency tunability (through control of electron energy) and mode competition in high power, large diameter (overmoded) devices. All these limitations can be eased by filling the corrugated structure with a column of plasma having a desirable radial profile and density. The influence of strongly magnetized plasma on the electromagnetic properties of both smooth [1]–[6] and corrugated [7]–[16] waveguides, as well as on the transport of relativistic electron beams [17]–[23] have been studied both theoretically and experimentally.

There are two advantages for injecting an electron beam into a waveguide filled with plasma. First it enhances the current carrying capability owing to the neutralization of the space charge fields, which is proportional to the parameter $\omega_p R_b/c$ [20], [21], where R_b is the radius of the beam, ω_p is the plasma frequency of the background plasma and c is the speed of light. In the case of $\omega_p R_b/c \gg 1$, the maximum propagating current is higher than the vacuum limiting value by a factor of $[(\gamma^2-1)/(\gamma^{2/3}-1)]^{3/2}$. Second, the plasma loading changes the electrodynamic properties, enabling controllable frequency upshifts [7], [10], [11]. An important step in recent years has been the discovery of the formation of hybrid modes combining the slow structure modes and the slow plasma modes. Hybrid modes can occur only if the magnetized plasma is of sufficiently high density, and its density is radially inhomogeneous. The slow plasma modes are characterized by strong fields near the axis of the slow wave structure, and for the slow structure modes strong fields are near the walls. Since the hybrid modes are formed at frequencies where the phase velocities of the two modes are nearly equal, it leads to a composite mode which has a strong field both at the plasma region and near the slow wave structure. Consequently, the hybrid mode strongly couples with an electron beam located far away from the structure. This mechanism may be responsible for enhanced interaction efficiency in plasma loaded slow wave structures.

Two properties of plasma loaded waveguides, namely greater beam current carrying capability and frequency upshifts have been observed in experiments where plasma loaded BWO's were driven by relativistic electron beams. Two approaches were used to fill the cavities with plasma. The first and earliest approach was to inject an electron

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beam into a corrugated cavity filled with neutral background gas [24]–[28]. In this case, a partly ionized plasma column was generated by beam impact ionization mostly along the beam transport channel. The results of those experiments could not be analyzed quantitatively because the most important parameters, the plasma density and its transverse profile, were not measured or defined. Moreover, the plasma density changes during beam injection, making quantitative interpretation most difficult. However, the results of these experiments showed qualitatively the two effects associated with plasma loading of BWO's as discussed above.

The second approach is based on filling the cavity with a preionized plasma column [29]–[33]. In our studies the plasma was generated by a pulsed plasma gun [31], [34] outside the microwave interaction region, and then injected along a strong, guiding magnetic field prior to beam injection. As a result, the plasma density in the cavity was easily and reproducibly tuned by changing the delay time between the plasma gun firing and beam injection. Furthermore, the plasma density and profile were measured directly [10], [11] and the density is not expected to change substantially during electron beam injection and microwave extraction. The results of plasma filled, relativistic (500 kV) BWO experiments based on this plasma filling approach were reported earlier [29], [32], in the operating regime of relatively low beam currents ($I_b < 500$ A) and moderate plasma densities $n_p < 10^{12}$ cm^{-3}.

The operation at high plasma densities ($n_p > 10^{12}$ cm^{-3}) in the interaction region proved difficult for two reasons. A high density plasma background, which is desirable in the corrugated interaction region, is undesirable in the diode and output regions. High plasma density can also cause deterioration in the electron beam quality and lead to a collapse of the diode impedance. The divergence of the guiding magnetic field at the output region results in a microwave absorption in the plasma layer where the upper hybrid resonance [3], [4] condition is satisfied. This is the case even if a high magnetic filed ($w_c \gg \omega_{\text{radiation}}$) is applied to the cavity region. A description of the special steps taken to protect both the diode and output regions are presented in Section II.

In this study, we report on a modified BWO filled with a radially inhomogeneous preionized high-density plasma, where both the output and diode regions of the system were protected to prevent the adverse plasma effects. The results of the experiments will be presented in Section III, while discussion and conclusions will be presented in Section IV.

II. Elimination of Plasma in the Output and Diode Regions

The experimental setup used for previous plasma-loaded BWO studies [31] is shown in Fig. 1. An annular relativistic electron beam created by a field emission diode is injected into a corrugated slow wave structure and collected in the output region. A uniform focusing magnetic field, generated by a pulsed solenoid, is used to confine both the beam and the plasma column. The plasma gun is located on the system's axis 40 cm away from the edge of the solenoid in the region of diverging magnetic field at the microwave extraction region.

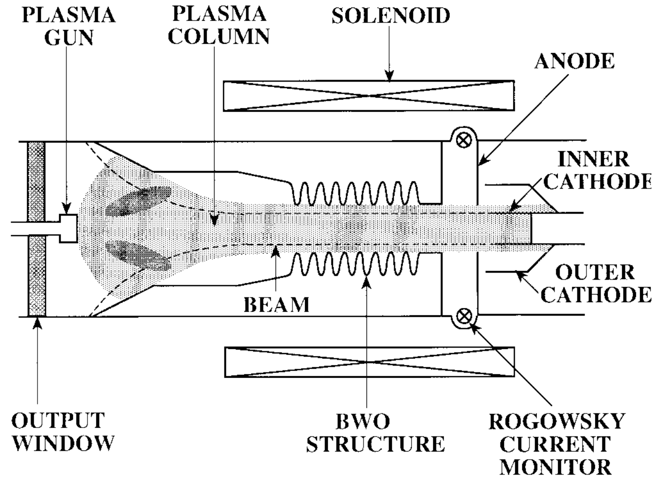

Fig. 1. Schematic diagram of a plasma-loaded BWO without protection against adverse plasma effect in diode and output regions. The electron beam, depicted by the broken line, is injected into the interaction region of the corrugated structure. The plasma hatched lightly is fired from the gun region. Microwave absorption by the upper-hybrid resonance is expected in the darkly shaded regions.

It is used to generate and inject the plasma into the system and create the plasma column. The plasma column in the region of the strong magnetic field has a bell shape radial profile with a characteristic radius $r_p \approx 1$ cm. The peak plasma density decays from a maximum plasma density of $n_p \cong 8 \times 10^{12}$ cm^{-3} with a characteristic decay time of 100–200 μs. By varying the delay time between the electron beam injection and the plasma gun firing, and by controlling the plasma gun operating voltage , the plasma density in the corrugated interaction region can be varied over a wide range, from $n_p \cong 10^9$ cm^{-3} up to 8×10^{12} cm^{-3}.

As briefly described in the introduction, the presence of high-density plasma ($n_p > 10^{12}$ cm^{-3}) in the interaction region, can create difficulties in the diode and output regions. In the output region the axial magnetic field decreases away from the solenoid. A resonant microwave absorbing layer will be created somewhere in the output region [3], [4] where the microwave frequency equals the upper hybrid frequency, i.e., $\omega^2 = \omega_p^2 + \omega_c^2$ (ω_c is the electron cyclotron frequency). This layer is capable of absorbing a considerable fraction of the output microwave energy and may also contribute to "microwave pulse shortening." On the opposite end of the system, plasma in the resonator may also stream into the diode region, where it can significantly reduce the diode impedance and cause deterioration in beam quality (spatial and longitudinal velocity distribution). This influence may be substantial for $\omega_p R_b / c > 1$. In our experimental setup, the plasma effects on the diode can be substantial for $n_p \leq 3 \cdot 10^{11}$ cm^{-3}.

In order to overcome those difficulties in the diode and output regions and still allow high-density operation in the corrugated interaction region, an improved experimental geometry was adopted as shown in Fig. 2. The plasma gun is mounted inside a long stainless steel tube extending into the uniform magnetic field region. This tube shields the output region from the magnetically active plasma and prevents absorption of microwave energy in this region. The relativistic diode

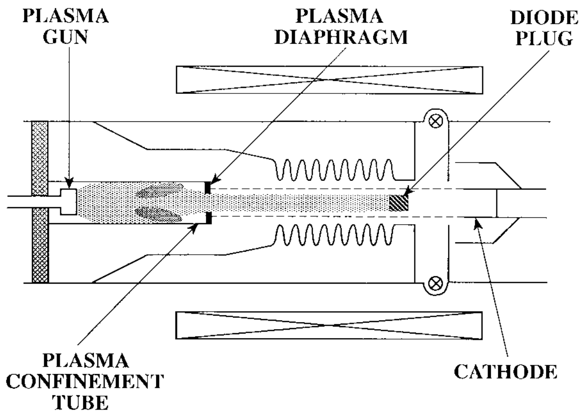

Fig. 2. A schematic diagram of an improved plasma-loaded BWO. The diode region is protected against the plasma by the diode plug. The upper-hybrid microwave absorption is almost completely eliminated

was protected by placing a cylindrical metallic "plug" (1.4 cm in diameter) close to the anode plane. This geometry allowed hollow beam propagation into the interaction region but prevented plasma penetration into the gun region. As a result, the improved experimental apparatus allowed us to investigate the influence of plasma density on BWO operation over a very wide density range without adversely effecting the diode and output regions.

Microwave power, microwave frequency spectrum, plasma density and plasma profile as well as diode and beam currents and diode voltage were routinely measured during the experiments. The microwave power was measured using a broad band hot carrier semiconductor detector (similar to that described in [35]) while the radiation spectrum was measured using a 71-m-long X-band dispersive waveguide. Diode voltage was measured with a capacitive voltage divider and beam current with a Rogowsky current monitor. The plasma was characterized by using a combination of a movable electron saturation current probe and a smooth-wall closed-cavity probe [10], [11] (see also Section IV).

First, the influence of plasma in the region of diverging magnetic field (output region) was studied. In previously obtained data [31], neither the output region nor the electron gun were protected against plasma penetration. Under those conditions ($B_z = 4$ kG, $I_b = 0.5$ kA, $V_b = 400$ kV) no adverse plasma effects were observed in the electron gun as long as $n_p \geq 3 \cdot 10^{11}$ cm^{-3}. However, the microwave generation efficiency, which peaked for plasma density in the range of 0.2–0.3 $\cdot 10^{11}$ cm^{-3}, decreased drastically for $n_p > 10^{11}$ cm^{-3}.

The results of a similar experiment ($B_z = 13$ kG, $V_b = 550$ keV, and $I_b \approx 500$ A) is shown in Fig. 3(a), and the same dramatic decrease in output power is observed for $n_p > 5 \cdot 10^{10}$ cm^{-3}. If the upper hybrid resonant plasma absorption of microwave energy does take place in the output region, then the elimination of the plasma in this region is expected to significantly improve the situation. Indeed, this is the case shown in Fig. 3(b). This data corresponds to an experimental BWO where the output region was shielded (see Fig. 2 for experimental set up), but no steps were taken to protect the field emission diode. No plasma effects are seen even for plasma densities of $n_p = 3 \cdot 10^{11}$ cm^{-3}. The frequency upshift due to the plasma ($n_p = 3 \cdot 10^{11}$) was measured to be $\Delta f \approx 0.5$ GHz. The results are in very good agreement with the measurements of the plasma influence on the dispersion diagram of corrugated cavities presented in Section IV. The flashover plasma gun was capable of generating peak plasma densities up to 3 $\cdot 10^{11}$ cm^{-3} when shielded, which is substantially less than the capabilities of unshielded version.

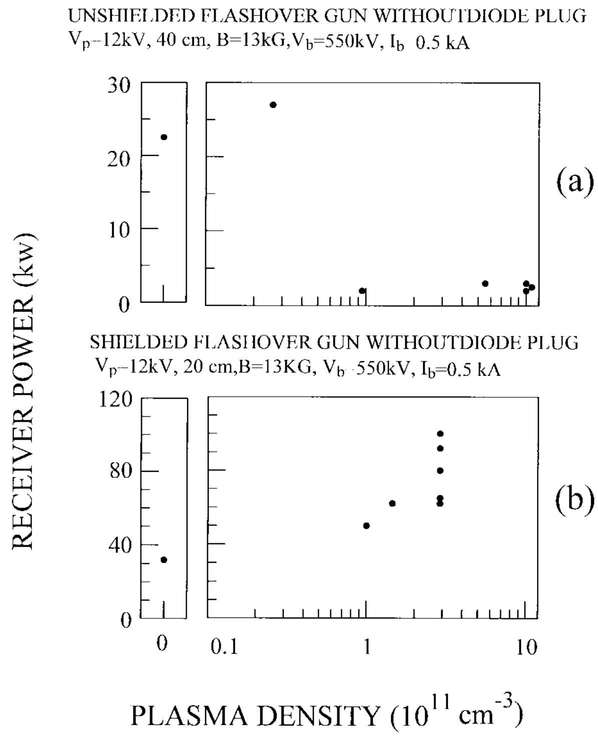

Fig. 3. (a) Microwave receiver power versus plasma density ($I_b = 500$ A, $V_b = 400$ kV, $B_z = 4$ kG, plasma gun voltage = 10 kV, 40 cm from the solenoid edge). The insert on the left shows the vacuum data. (b) Same as (a) except that the plasma gun was shielded by a metallic tube to prevent the upper hybrid resonance absorption in the output region. (see Fig. 2). Plasma gun voltage 12 kV, positioned 20 cm from the solenoid edge. The insert on the left shows the vacuum data.

Second, the plasma influence on the operation of the relativistic field emission diode was studied. High plasma densities, up to 8 $\cdot 10^{12}$ cm^{-3}, were achieved when the shielded flashover plasma gun was replaced by an upgraded shielded coaxial plasma gun. Plasma penetration into the diode region leads to a change in the beam current waveform. In the presence of a high-density plasma, an initial, short (30 ns) current spike was superimposed on the normal (100 ns) rectangular pulse typical for diode operation in vacuum or low-density plasma. Fig. 4(a) shows the peak amplitude of this spike as a function of the plasma density. From the figure it is clear that the higher the plasma density, the higher the peak current. For a plasma density of 3 $\times 10^{11}$ cm^{-3} the beam current is almost equal to that in vacuum, in agreement with the estimation described in the introduction. At that plasma density, the field emission diode is substantially affected by the plasma, but the received microwave power is still increasing with increased beam current, as shown in Fig. 4(b).

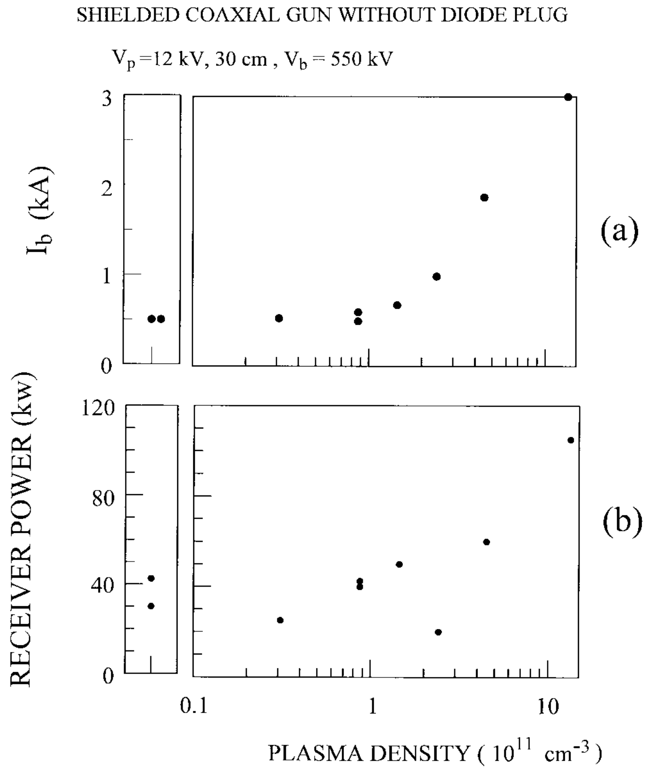

Fig. 4. Experimental results of a plasma loaded BWO, where the diode region is not protected against plasma penetration. $V_b = 550$ kV. (a) beam current versus plasma density. (b) Microwave receiver power versus plasma density. A coaxial plasma gun shielded by a metallic tube was used to prevent the hybrid cyclotron absorption in the output region. The insert on the left shows the vacuum data.

To access even higher plasma density in the interaction region, the field emission diode must be protected. This was successfully achieved by using a cylindrical, 1.4-cm-diameter “plug” held by two thin support plates and positioned inside the injection tube, upstream from the anode. The plug stopped the plasma flux into the diode without interfering with beam $(r_b = 0.8$ cm) injection. Under these conditions the diode operated normally even when the peak plasma density in the interaction region was as high as 8 $\cdot 10^{12}$ cm^{-3}.

In conclusion, by eliminating plasmas in both the output and diode regions it was possible to investigate the effects of high plasma density in the corrugated interaction structure independently.

III. Relativistic BWO Operating with a High Background Plasma Density

In the modified BWO described in this section both the output region and the relativistic diode were protected against plasma penetration (a shielded coaxial plasma gun was used). Dependencies of power and spectrum of the output microwave radiation on plasma density in the corrugated cavity region were studied. Experiments were performed at two beam currents of 0.5 and 0.8 kA and an electron energy of 550 keV. As mentioned earlier, the spectrum of radiation was measured using a X-band dispersive waveguide of 71 m length. A microwave pulse reaching the dispersive line input is recorded as a prompt signal by using a broadband detector.

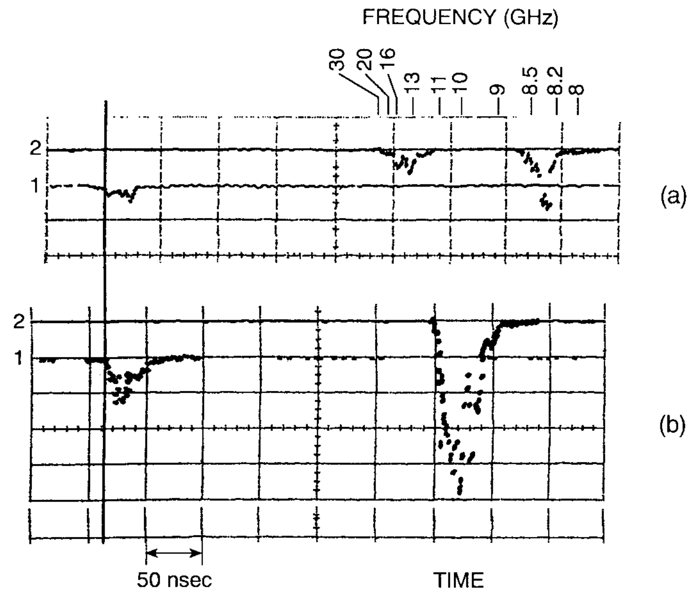

Fig. 5. The prompt and dispersed microwave signals of a modified vacuum and plasma-loaded BWO. Dispersive waveguide length 71 m. (a) Vacuum case. The dispersed signal contains the two frequency bands of $TM_{01}, f = 8.5$–8.7 GHz, and TM_{02}, TM_{03} GHz i.e., overmoded operation. (b) Peak plasma density of $n_p = 2.4 \times 10^{12}$ cm^{-3}. In the dispersed signal only the up-shifted TM_{01} band was observed. The upper bands of TM_{02}, TM_{03} were suppressed by the presence of plasma.

The microwave pulse propagating in the dispersive line is decomposed into its spectral components (due to the frequency dependence of group velocity) and is also recorded. As a result, the spectrum of the microwave pulse is converted into differences in a delay time between the prompt and output signals. This spectral diagnostic technique is accurate enough if the original microwave pulse duration is much smaller than the delay time. Fig. 5 shows an example of the oscillograms of a prompt “1” and dispersed “2” signals. Fig. 5(a) and (b) correspond to the vacuum and plasma filled cavity with plasma density of 2.4 $\cdot 10^{12}$ cm^{-3}, respectively. In Fig. 5(a) the spectrum of the radiation contains two separate regions: the lower, $f = 8.5$–8.7 GHz and the higher, $f = 17$–27 GHz. These ranges correspond to the uncertainty due to the spectral width. The lower frequency radiation $(f = 8.5$ GHz) corresponds to the excitation of TM_{01} mode of the BWO with a 550-KeV electron beam, while the higher frequency band of 17–27 GHz includes the excitations of TM_{03} with $f \sim 18$ GHz. Fig. 5(b) shows upshifts of the TM_{01} mode frequency (10.5–11.5 GHz) and suppression of the TM_{02} and TM_{03} modes for the case of a dense plasma $n_p = 2.4 \times 10^{12}$ cm^{-3}.

The dependence of the radiated frequencies on plasma densities is summarized in Fig. 6(a), where the bars represent the accuracy of the dispersive line technique. It shows drastic change in the spectrum of radiation in the region of $n_p > 10^{12}$ cm^{-3}, in which the TM_{01} band is up shifted while the higher order modes are suppressed [see also Fig. 5(b)]. This means that the loading of a high-density plasma may help the suppression of undesired high-order modes in high-power large-diameter overmoded systems.

In addition to the microwave measurements with the long dispersive line, we directly measured microwave power at

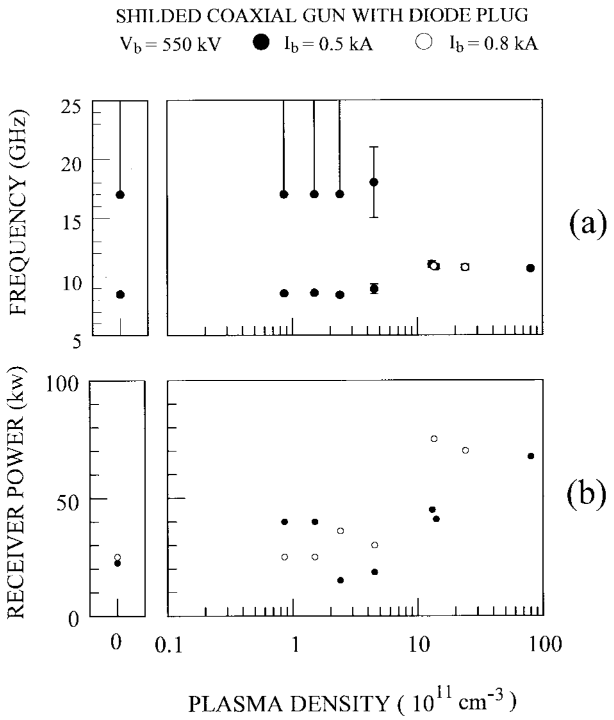

Fig. 6. Measured microwave frequency and power as a function of the plasma density in the interaction region of a modified plasma-loaded BWO. Both output and diode regions were protected. (a) Output frequency versus peak plasma density. (b) Microwave received power versus peak plasma density. For $n_p > 10^{12}$ cm^{-3}, the lower frequency band is up-shifted while the upper bands were suppressed as indicated in Fig. 5. The insert on the left shows the vacuum results. Beam current and the plasma gun parameters are shown in the figure.

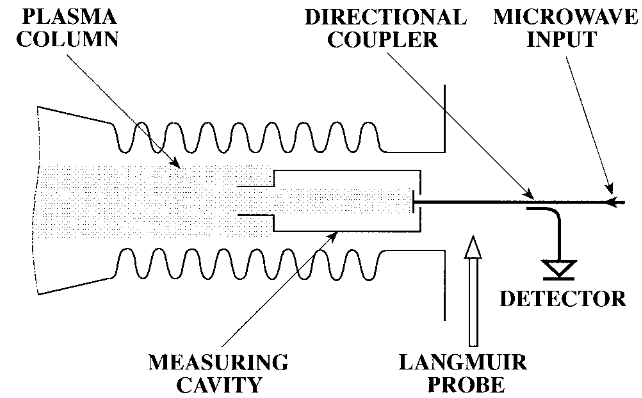

Fig. 7. A Schematic diagram of the plasma density measurement apparatus inside the corrugated structure. The combination of the smooth wall cavity with a long Langmuir probe was used to measure transverse plasma profile and plasma density.

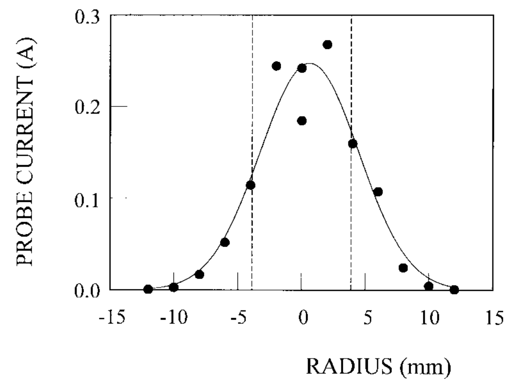

Fig. 8. A typical example of the transverse plasma density profile inside the corrugated cavity. The ordinate and abscissa are the probe currents and the radius from the center of the plasma column, respectively.

the output window of the BWO with a calibrated hot carrier similar to those described in [35] and [36]. This receiver has a sensitivity of about 0.2 V/kW. The dependence of output power on plasma density is shown in Fig. 6(b), where the solid and hollow circles represent electron beam currents of 0.5 and 0.8 kA, respectively. These two different beam currents generated by adjusting the cathode geometry (the axial position of the inner cathode with respect to the outer cathode in the electron gun). In both cases the presence of a high-density plasma did not affect the beam current at all. It is noted that the measured microwave output power for $n_p > 10^{12}$ cm^{-3} is three times higher than its vacuum counterpart.

IV. Measurements of the Characteristics of Corrugated Cavities Filled with High Plasma Density

The techniques used to measure the transverse plasma profile and plasma density were described earlier [10], [11]. The plasma density profiles were measured next to the beam injection port of the corrugated structure as a radial dependence of electron saturation current with a long movable Langmuir probe. The apparatus is shown in Fig. 7. A typical example of the plasma profile at 100 μs after plasma firing is shown in Fig. 8, where a shielded coaxial plasma gun charged to 12 kV and a 13 kG guiding magnetic field were used. In the figure, the ordinate and abscissa represent the probe current (A) and the distance from a chord of the probe to the center of the cavity, respectively. The plasma profile has a bell shape with half width radius of 0.4 cm. A special code calculates plasma densities for a finite guiding magnetic field from the measured plasma profiles and the temporally resolved resonant characteristic of a small smooth-wall cavity. This smooth-wall cavity was inserted into the corrugated structure after removing the probe as shown in Fig. 7.

Fig. 9 shows the temporal behavior of peak plasma density in the corrugated cavity. The plasma density increased during the first 60 μs to reach a maximum of 8 $\cdot 10^{12}$ cm^{-3} (plasma gun voltage 20 kV) followed by decrease with decay time in the range of 50–200 μs. The plasma loading influence on frequency upshifts of the corrugated cavity is shown as a function of plasma density in Fig. 10. In the figure, the solid circles represent TM_{01n} axial modes of the corrugated cavity, where the mode number n increases from right to left for a fixed frequency. One can see that the higher plasma density gives a larger upshift of resonant frequencies. The maximum plasma density in which the resonances were resolved is around 2 $\cdot 10^{12}$ cm^{-3}, corresponding to a maximum frequency of about 11.5 GHz. The number of measured resonances in the plasma loaded cavity depends on the externally applied frequency and the plasma density. In the frequency range between 8.9 and 9.25 GHz, the determination of the individual axial modes is possible because all the eight resonances of an

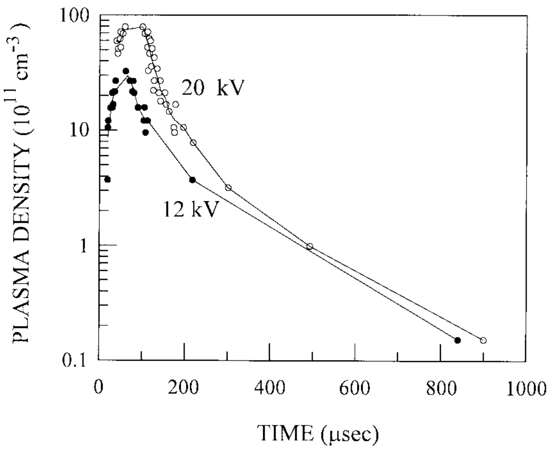

Fig. 9. Temporal behavior of the peak plasma density in the corrugated cavity. It reached the maximums of 3×10^{12} cm^{-3} and 8×10^{12} cm^{-3} with a coaxial plasma gun charged to 12 and 20 kV, respectively under $B_0 = 13$ kG.

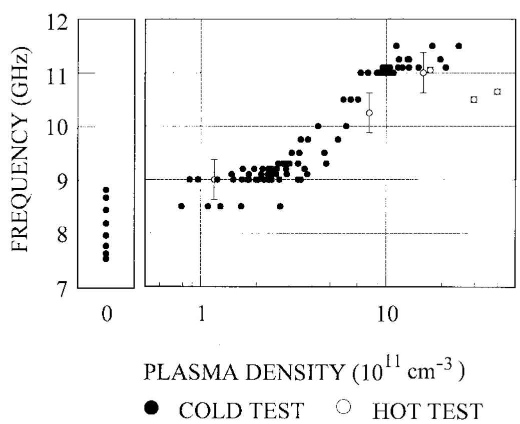

Fig. 10. The plasma influence on the electrodynamic properties of a corrugated cavity. The measured frequencies of the axial modes of a plasma loaded corrugated cavity (solid circles) are plotted as a function of peak plasma density. Open circles are the results of hot test experiments with an electron beam. The insert on the left shows the measured frequencies of the eight axial modes associated with a corrugated cavity without plasma loading.

eight and half periods slow wave structure with an open end were available. However over 9.5 GHz the determination is increasingly more difficult because not all eight resonances were observed. The decrease in the number of the observed resonances is a consequence of flattening dispersion curves of the corrugated structure for high plasma density. The flattening also reduces the frequency passband (upper cutoff to lower cutoff) of the corrugated cavity as demonstrated in Fig. 10. For an evacuated structure the passband is 1.28 GHz, while for a structure loaded with high plasma density $(n_p > 10^{12}\ \mathrm{cm}^{-3})$, the passband is 0.4 GHz. The open circles in Fig. 10 are the results of hot test experiments with relativistic electron beams.

V. Summary and Discussion

An experimental study of a modified relativistic (500 kV, 500 A) BWO filled with a radially nonuniform, preionized, high density $(8 \cdot 10^{12}\ \mathrm{cm}^{-3})$ plasma column is described.

The adverse effects of plasma on plasma loaded devices are mainly the reduction of impedance in diode regions and microwave absorption due to upper hybrid resonance layers in output regions. In our new system we succeeded in preventing these effects, which allowed us to investigate the operation of a BWO in the high plasma density regime.

In our studies, a BWO filled with a high-density plasma showed 30% frequency tunability (8.4–11 GHz) by changing the background plasma density (up to $n_p = 8 \cdot 10^{12}\ \mathrm{cm}^{-3}$). Also, the excitation of higher order modes $(\mathrm{TM}_{02}, \mathrm{TM}_{03})$ was suppressed in the high-density regime $(\omega_c > \omega_p > \omega)$. This is a promising approach for achieving single mode operation of high-power large-diameter overmoded devices loaded with plasmas. In addition, the presence of a high-density radially inhomogeneous plasma $(n_p > 10^{12}\ \mathrm{cm}^{-3})$ can lead to the formation of hybrid modes with strong beam-wave coupling far from the structure walls [4], [7], [8]. In fact, our experiment shows in this regime a substantial increase in microwave output power over a vacuum device under the same operating conditions.

The next step in our program is to study BWO operation at plasma densities of up to 10^{14} cm^{-3} and high current beams (several kiloamps), including operation above the vacuum limiting current. This will be followed by studies of a high-current relativistic beam in a large-diameter overmoded BWO filled with a high-density radially inhomogeneous plasma.

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L. Duan, photograph and biography not available at the time of publication.

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