Study of a Large Diameter Backward Wave Oscillator without Guiding Magnetic Field

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Abstract

A large diameter backward wave oscillator (BWO) without guiding magnetic field is demonstrated experimentally. The beam propagation is achieved by filling SWS with helium gas. The oscillation mode of the BWO might be the axisymmetric TM mode as well as TE mode. The output power of the TM mode is less than 1kW, which corresponds to electronic efficiency less than 0.004 %. At zeo-magnetic field, the conventional Cherenkov and cyclotron interactions are degenerate and perturbed beam motions perpendicular as well as parallel to an axial direction should be taken into account. In the degenerate beam interaction, surface charge σ_1 at beam-vacuum boundary plays essential role. Numerical analysis shows that the degenerate interaction is superior to the conventional Cherenkov interaction in the high current region above 100 A and in the weakly relativistic energy region.

Keywords: Backward wave oscillator, Slow wave structure, Cherenkov interaction, Cyclotron interaction, Degenerate interaction

1. Introduction

Extensive efforts have been devoted to developing high power Cherenkov devices, including the backward wave oscillator (BWO).[1, 2] BWO can be driven by an axially injected electron beam without initial perpendicular velocity and are particularly suited to operation with an intense electron beam. However, in order to confine an intense electron beam, a strong axial magnetic field has been used. Due to field coils, devices have become heavy and complicate. A high power BWO without guiding magnetic field (plasma-assisted slow wave oscillator) have been demonstrated as a compact, efficient and lightweight high-power microwave device.[3] Oscillation frequencies are in the range up to X-band. TE as well as TM mode radiations were observed. In the plasma-assisted slow wave oscillator, the electron beam propagation was achieved by utilizing the background plasma.

Plasma effects in vacuum microwave devices have been studied experimentally and theoretically. One common effect is neutralization of beam charge by the background plasma, allowing beam propagation in the slow wave device well above the space charge limited current. The plasma can also enhance the microwave output power of TM mode.[4-6] Although this plasma effect has been studied extensively, most analyses have considered only the one-dimensional (longitudinal) perturbed motion of the beam electron. Moreover, plasma effect on TE mode radiation from BWO's with and without magnetic field have not been clear.

In this report, the beam interaction with axisymmetric TM mode at zero-magnetic filed is examined. In the zero-magnetic filed case, the conventional Cherenkov and cyclotron interactions are degenerate and perturbed beam motions perpendicular as well as parallel to a finite magnetic field should be taken into account. The degenerate interaction in a periodically corrugated waveguide is presented. And then, we demonstrate a large diameter BWO without guiding magnetic field experimentally.

2.Beam interaction with axisymmetric TM mode at zero-magnetic field

For a magnetized electron beam, there exist three distinct beam modes, those are the slow ($\omega = k_z v_0 - \Omega/\gamma$) and fast ($\omega = k_z v_0 + \Omega/\gamma$) cyclotron modes and the Cherenkov mode ($\omega = k_z v_0$). Here, ω is the angular frequency of the perturbing electromagnetic field, $\Omega = eB_0/m_0$, m_0 and $-e$ are the non-relativistic cyclotron angular frequency, the rest mass and the charge of an electron, respectively, and γ is the relativistic factor. At zero-magnetic field, the cyclotron modes and the space charge modes become degenerate. In this case, the vertical beam motion is not restricted by the magnetic field. The change in the volume density ρ_1 caused by the longitudinal current is cancelled by the change caused by the vertical current. Therefore, there is no coupling due to ρ_1 between the beam and the axisymmetric TM mode and the surface charge σ_1 at the beam-vacuum boundary plays essential role in the degenerate interaction.[7]

The result of numerical analysis of degenerate interaction in a typical X-band slow wave structure (SWS) is shown in Fig.1, in which temporal growth rates are plotted by solid line (degenerate interaction) and dashed line (conventional Cherenkov interaction). The growth rate of the degenerate interaction becomes maximum around the beam energy 200-300 keV with beam current 100 A, Fig.1(a), and increases with increasing the beam current with beam energy 300 keV, Fig.1(b). It should be pointed out that the degenerate interaction is superior to the conventional Cherenkov interaction in the high current and the weakly relativistic energy regions.

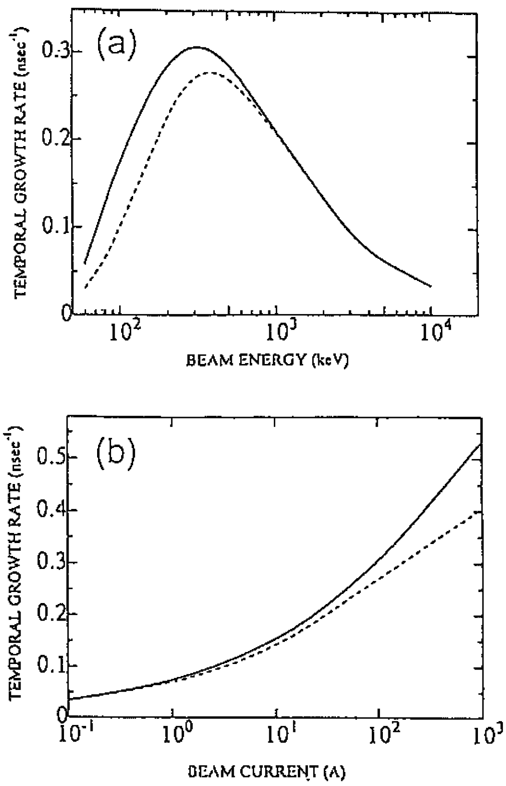

Fig.1 Comparison between degenerate and conventional Cherenkov interaction.

3.Experiment

Our BWO is schematically shown in Fig.2. The electron beam diode, the SWS and the beam collector are installed in a stainless steel vacuum vessel. The parameters of the SWS are as follows; average radius R_0=30 mm, corrugation amplitude h=1.7 mm and pitch length z_0=3.4 mm. These parameters are chosen so as to increase the oscillation frequency of fundamental TM_{01} mode up to 20 GHz. The total length L=70z_0=238 mm. This SWS is oversized with the mean diameter four times larger than the free space wavelength of the microwave output for TM_{01} mode.

Output voltage up to about 80 kV from a pulse-forming line is applied to a cold cathode. The axisymmetric emitting edge of the cathode is wrapped with velvet. An anode is copper mesh. The diode voltage is measured by a resistive voltage divider. For measurements of diode current, a Rogowski coil is placed between the cathode and the anode. Receiving antenna is a rectangular horn antenna. The coupling coefficient between output window and receiving antenna is determined by a vector

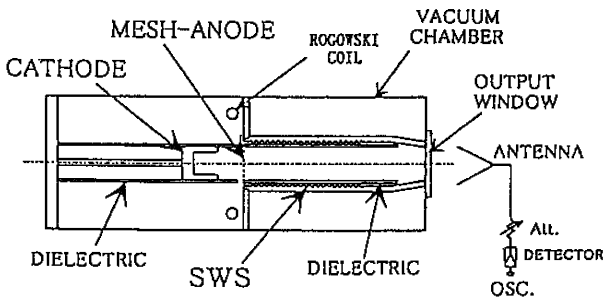

Fig.2 Schematic diagram of the large diameter BWO.

network analyzer for a circular TM_{01} mode. The absolute value of the output power of TM_{01} is estimated by using this coupling coefficient. Received signals are split into two branches by a multi-hole directional coupler. One consists of a short waveguide and forms a prompt signal. The other is a delay line waveguide typically 6 m long and forms a delayed signal. The signal frequency is able to estimate from the delayed time.

In this report, SWS is filled by helium gas. The electron beam propagation is monitored by a beam collector at various axial positions as shown in Fig.3. The beam collector is made of a stainless plate. Without helium gas (solid circle), beam current decreases with increasing axial distance from the anode. At the filling pressure p_{He}~80 mtorr (double circle), beam can propagate up to about 120 mm from the anode.

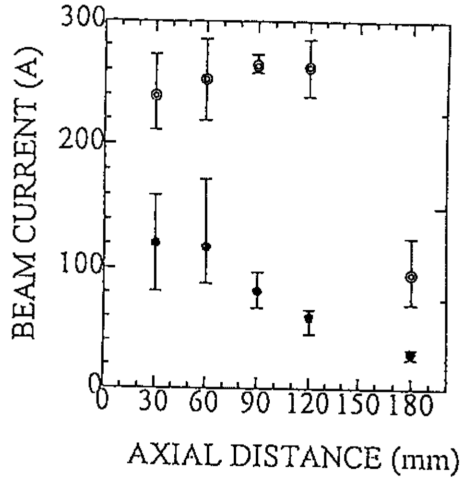

Fig.3 Beam propagation characters.

The output power from the large diameter BWO strongly depends on p_{He} as is shown in Fig. 3. The diode voltage and current at the peak of microwave signal are about 36 kV and 2000 A, respectively. At relatively low p_{He}, less than about 80 mtorr, no meaningful microwave power is observed. The microwave power increases sharply with p_{He}~120-130 mtorr. Maximum detected power is in the 1 W range. When the SWS is replaced by a straight cylindrical waveguide, the detected power remains in the noise level even in the pressure range p_{He}~120-130 mtorr. In Fig.3, the delay time of a delaied signal is about 40 nsec and the frequency is estimated to be about 20 GHz.

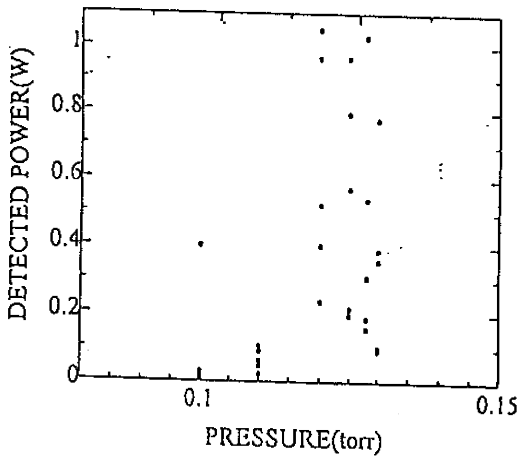

Fig.4 Detected microwave power versus filling pressure.

The preliminary radiation patterns are measured by moving the receiving antenna vertically with vertical and horizontal electric polarization. The pattern with the vertical polarization shows the axisymmetric TM mode radiation. The pattern with the horizontal polarization shows that TE mode comparable to the TM mode is radiated. The output power of the TM mode is less than 1kW and the corresponding electronic efficiency is less than 0.004 %.

4.Discussion and Conclusion

Without guiding magnetic field, the cyclotron modes and the space charge modes become degenerate and the surface charge σ_1 at the beam-vacuum boundary plays essential role. For our large diameter SWS with periodically corrugated wall, the degenerate interaction is superior to the conventional Cherenkov interaction in the high current region above 100 A and in the weakly relativistic energy region.

A large diameter BWO without guiding magnetic field is demonstrated experimentally. The beam propagation is achieved by filling SWS with helium gas. The oscillation mode of the BWO might be the axisymmetric TM mode as well as TE mode. The output power of the TM mode is less than 1kW, which corresponds to electronic efficiency less than 0.004 %.

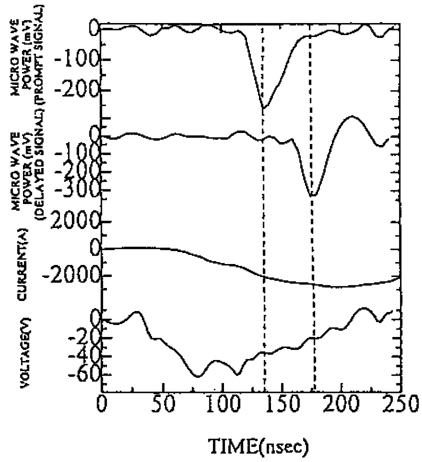

Fig.5 Wave forms of prompt and delayed signals of microwave power, beam current and beam voltage.

The TM mode radiation might be attributed to the degenerate interaction between the beam and the structure TM mode. TE mode radiation has also been observed in BWO,s with guiding magnetic field and has frequently be attributed to the cyclotron interactions. In our large diameter BWO, there is no magnetic field, which introduce the cyclotron interactions. There might be several possible TE mode radiation mechanisms, such as hydrodynamic beam-plasma interaction and vertical beam trajectories proposed in ref.3. Since the TE modes observed is seen like non-axisymmetric in our experiment and in ref.3, we point out that the hybrid mode interaction might be important. A self-consistent analysis of hybrid mode interactions is presently underway and will be presented in a future paper.

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