Proceedings of ITC18, (2008)

Experimental Study on Performance of Slow Cyclotron Maser in Weakly Relativistic Region

K. Bansho, K. Ogura, H. Oe, Y. Kazahari, H. Iizuka, A. Sugawara

Graduate School of Science and Technology, Niigata University, Niigata 950-2181, Japan

[a] *Plasma Research Center, University of Tsukuba, Tsukuba 305-8577, Japan*

(Received day month year / Accepted day month year should be centered 10-point type)

Studies of slow cyclotron maser operation of slow–wave device are reported. The beam voltage is weakly relativistic, less than 100 kV. The slow-wave structure is periodically corrugated oversized waveguide, whose target operation frequency due to the Cherenkov interaction is in K-band. By using rectangular corrugation having the relatively small ratio of corrugation width to periodic length of about 20%, the dispersion curve around the upper cut-off becomes flat and the effect of second harmonic slow cyclotron resonance is observed in the low energy region near 30kV. By using the sinusoidal corrugation and the rectangular corrugation having the ratio of corrugation width to periodic length of 50%, the effect of the fundamental and the second harmonic slow cyclotron maser is observed in the low energy region.

Keywords: slow-wave device, weakly relativistic region, rectangular corrugation, slow cyclotron maser

1. Introduction

Backward wave oscillators (BWOs) are one of high-power microwave sources. In BWO, a slow wave structure (SWS) is used to reduce the phase velocity of electromagnetic wave to beam velocity. Axially streaming electron beam interacts with the electromagnetic field to generate high-power microwaves. In order to increase the power handling capability and/or the operating frequency, oversized SWS have been used successfully. The term “oversized” means that the diameter D of SWS is larger than free-space wavelength λ of output electromagnetic wave by several times or more.

In Ref. [1], the combined resonance operation of the Cherenkov interaction and the second harmonic slow cyclotron interaction is reported by using rectangularly corrugated SWS. Although the radiations based on the conventional Cherenkov interaction are predicted to be independent of the magnetic field strength, some strong magnetic field dependence of output power can be seen. The electromagnetic field properties of beam in a finite strength magnetic field are still far from being fully elaborated. And the magnetic field dependence of slow-wave device is a still unsettled issue. In this study, we investigate how operating characteristics of slow-wave devices are depend on the magnetic field from a viewpoint of slow cyclotron interaction.

2. Slow Wave Structure (SWS)

The cylindrical SWS is periodically corrugated. The corrugation is rectangular or sinusoidal. In Fig.1, the rectangular SWS is shown. Dispersion characteristics of SWS are determined by the average radius R_0, corrugation amplitude h and periodic length z_0. The corrugation wave number is given by $k_0=2\pi/z_0$. For the rectangular SWS, one more parameter is added, that is, the corrugation width d. The dispersion characteristics of structure are controlled by changing R_0, h, d and z_0.

Dispersion curves of rectangular SWS are obtained by a numerical method based on the mathematical formula in Ref. [2]. Figure 2 shows the dispersion relation of fundamental axisymmetric transverse magnetic (TM_{01}) mode for two types, whose parameters are listed in table 1. In Fig.2, beam lines of space charge mode $\omega= k_z v$ and slow cyclotron mode $\omega= k_z v-\Omega$ are also plotted. Here, ω, k_z, v and Ω are angular frequency, axial wave number, beam velocity and relativistic cyclotron frequency, respectively. The slow space charge and the slow cyclotron modes couple to fundamental TM_{01} mode, leading to the Cherenkov and slow cyclotron instabilities. For A parameter, the slow-wave device operates as BWO based on the Cherenkov instability by 80 keV beam. The beam interaction point with TM_{01} is close to the upper cut-off at π -point. For B parameter, the dispersion curve around the upper cut-off becomes flat. And the interaction point

author’s e-mail: f08e078g@mail.cc.niigata-u.ac.jp

between the 80 keV slow space charge mode and TM_{01} mode shifts toward a traveling wave region. Decreasing beam energy to 30 keV, the interaction point moves to a backward wave region as shown in Fig.2.

Table 1 Parameters of rectangular SWS

	R_0 [mm]	h [mm]	z_0 [mm]	d/z_0 [%]
A	15.1	1.1	3	50
B	15.38	1.38	2.2	22.7

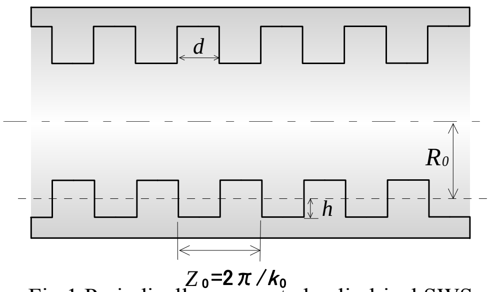

Fig.1 Periodically corrugated cylindrical SWS.

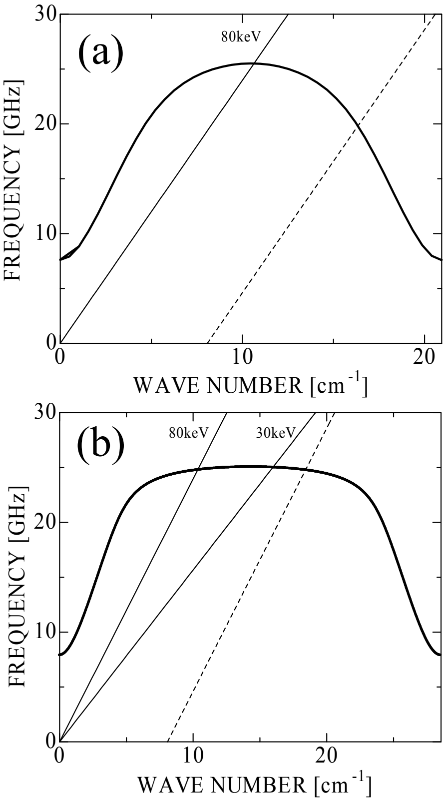

Fig.2 Dispersion characteristics of TM_{01} for rectangular SWS, (a) for A type SWS and (b) B type SWS. Solid lines and dashed lines are slow space charge mode and slow cyclotron mode, respectively.

Dispersion curves like Fig. 2(a) are obtained by sinusoidal corrugations. However, the flat pattern like Fig. 2(b) requires relatively small value of d/z_0 and cannot be realized by sinusoidal corrugations. In this paper, the dispersions like Fig. 2(a) and 2(b) are called A type and B type, respectively. In Fig.3, a photograph of B corrugation is shown. We examine the performance of slow cyclotron maser in the weakly relativistic region using rectangular corrugated SWS and sinusoidal corrugated SWS.

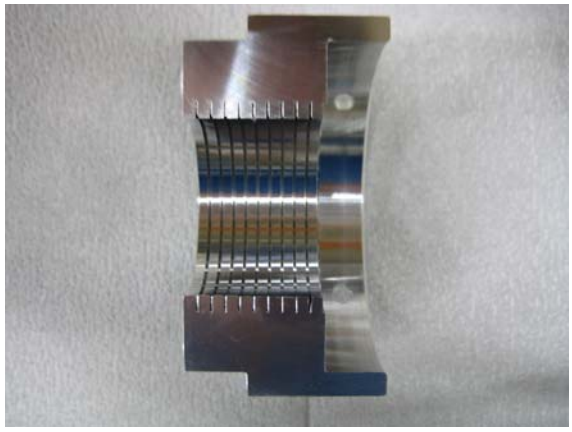

Fig.3 Rectangular corrugation of type B.

3. Experimental results

The experimental setup is schematically shown in Fig.4. Output voltage up to 100 kV from the pulse forming line is applied to the cold cathode. A disk cathode proposed in Ref. [3] is used as a cold cathode. A uniform axial magnetic field B_0 for the beam propagation is provided by ten solenoid coils. The value of B_0 can be changed from zero to about 1T. The microwave outputs are picked up by a rectangular horn antenna typically located 600 mm away from the output window.

Figure 5 shows an example of detected signals. The beam voltage and current are about 100kV and 300A, at the microwave peak time. The microwave signal is split into two branches. One consists of a short waveguide and forms a prompt signal. The other branch is a delay line and forms a delayed signal. The operation frequency estimated from delay time is about 26GHz.

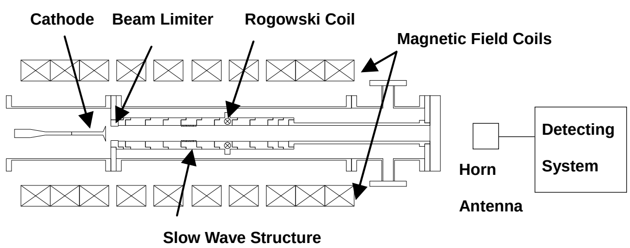

Fig.4 Schematic diagram of the experimental setup.

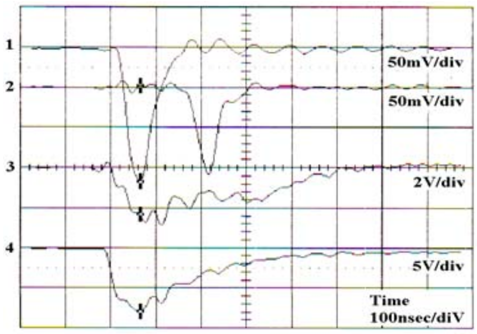

Fig.5 Waveform of measured signals: 1 prompt signal, 2 delayed signal, 3 beam current and 4 beam voltage.

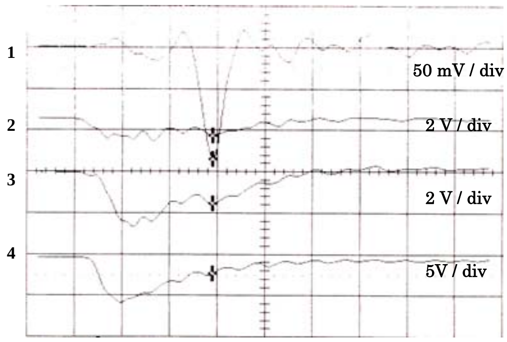

Fig.6 Waveform of measured signals: 1 microwave output, 2 cathode current, 3 beam current and 4 beam voltage.

There exists a critical beam voltage for the meaningful radiations based on the Cherenkov interaction [4]. The starting voltage is more critical than the starting current for the oversized BWOs. Figure 5 corresponds to the radiation above the starting voltage for A type.

Figure 6 is an example of the waveform of measured signals for B type. Microwave radiations like A type are not observed. In Fig.6, the applied beam voltage is about 75kV. However, no radiation starts until the voltage decreases to 30kV. As explained in the previous section (Fig.2), the space charge mode intersects in the travelling wave region with the beam voltage above about 60 keV. And hence, BWO operation based the Cherenkov interaction will not start. The oscillation mechanism rather than the Cherenkov works. Figure 7(a) is a power dependence on B_0 for B type SWS. The radiation resonantly increases at about 0.65 T. This may be the effect of slow cyclotron interaction, as discussed later.

For Fig. 7(a), disks corresponding to rectangular corrugation are fabricated and are integrated into one piece. The manufacturing accuracy may be inferior. The accuracy may be improved by fabricating the corrugation as one piece. Figure 3 is the improved corrugation with a manufacturing accuracy of the order of 0.01mm. Figure 7(b) is power dependence on B_0 by using the improved SWS. Compared with Fig.7(a), the microwave output increases about three times.

By changing the condition at SWS end, the radiation mode can be controlled as reported in Refs. [1,3]. For Figs.7(a) and (b), a straight cylinder with 68 mm is placed at the beam entrance of SWS. The radiation patterns are measured and show the radiation mode is nonaxisymmetric hybrid HE_{11} mode for Fig.7. By changing the cylinder length before SWS to 34mm, the radiation mode changes to axisymmetric TM_{01} mode. The power dependence on B_0 becomes like Fig.8. The effect of slow cyclotron interaction is observed above 0.6 T. However, the outputs decrease around 0.7 T. This might be caused by the effect of the absorption due to the fast cyclotron interaction in the straight cylinder before and after SWS as discussed latter.

In Fig.9, the power dependence on B_0 for sinusoidal corrugation is shown. The microwave outputs become a peak at about 0.9 T and 0.45T. This might be caused by a resonance between slow cyclotron and Cherenkov interactions. For rectangular corrugated SWS with the ratio of corrugation width to periodic length of 50%, similar power dependence on B_0 is observed. However, the fundamental operation is not clear compared with the sinusoidal corrugation.

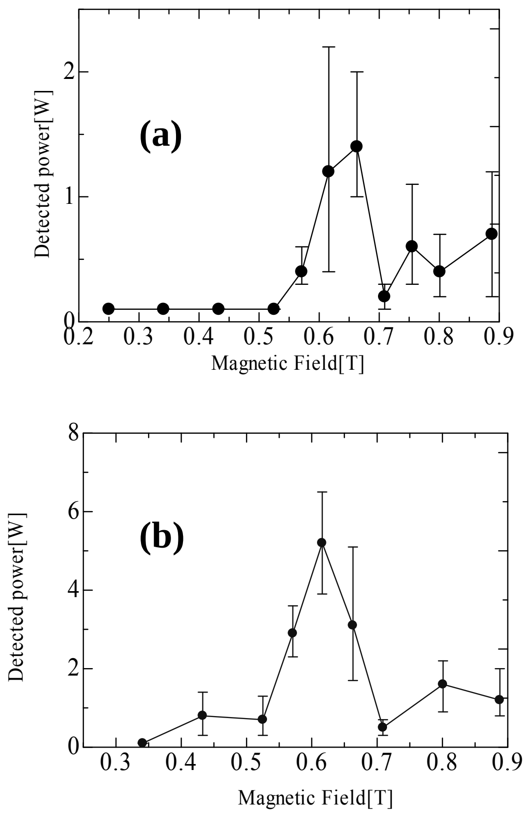

Fig.7 Output powers versus the magnetic field for a 10-period B SWS. The upper is the disk-integrated SWS and the lower is the improved SWS. The beam voltage is about 30kV.

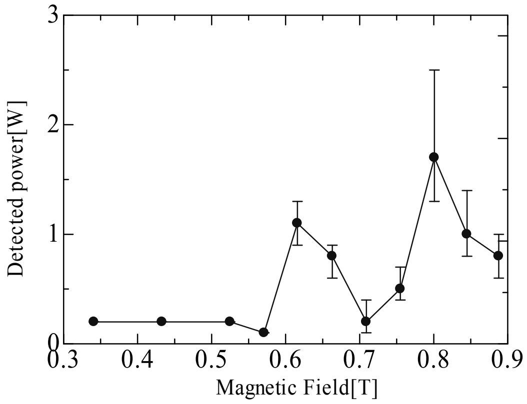

Fig.8 Output powers versus the magnetic field for a 10-period SWS of B type. The beam voltage is about 30kV.

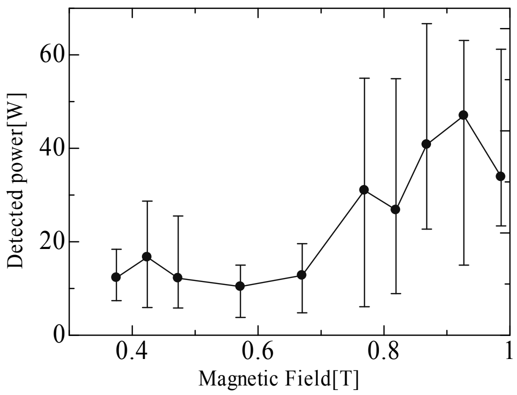

Fig.9 Output powers versus the magnetic field for a 50-period sinusoidal corrugated SWS. The beam voltage is about 40kV

4. Discussion and Conclusion

The dispersion curve of axisymmetric TM_{01} mode for sinusoidal corrugated SWS is shown in Fig.10. Beam space charge effects are included in the Cherenkov interaction, using a field theory based on an infinitesimally thin annular beam in Ref. [5]. The slow cyclotron mode depends on the axial magnetic field B_0. By increasing B_0, the beam line of slow cyclotron mode $\omega = k_z v - \Omega$ shifts to the right in Fig.10. The Cherenkov interaction synchronizes resonantly with the slow cyclotron interaction at the fundamental frequency around 0.84T. This is a slow cyclotron maser operation reported in Refs. [6, 7]. The output peaks in the region of 0.9 T and 0.45 T in Fig.9 respectively correspond to the combined resonance operation at the fundamental and the second harmonic frequencies of slow cyclotron interaction.

For B type, the combined resonance occurs at 1.25 T. In Fig.7, the outputs increase around 0.6 T can be explained by the combined resonance of the Cherenkov interaction and the second harmonic slow cyclotron interaction.

In Fig.8, the microwave power is once increased around 0.6 T. In this case, the absorption by the straight cylinder before and after SWS is occurred around 0.7 T in addition to the amplification due to the combined resonance. In Fig.8, the absorption is stronger than the amplification and the microwave power is decreased. It is necessary to control the absorption effect as well as amplification effect. More definite study of the synergistic interaction should be required.

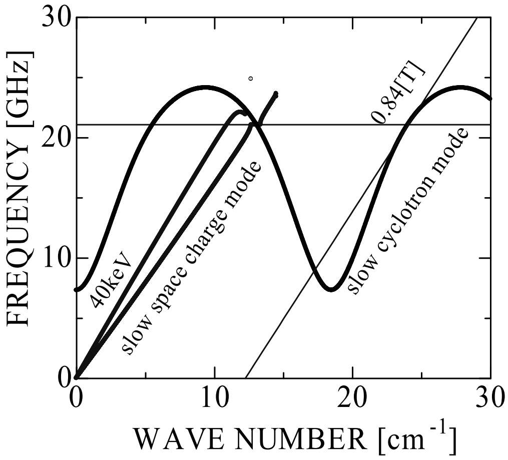

Fig.10 Dispersion curves of fundamental TM_{01} for type B SWS. The beam energy is 40 keV.

Acknowledgments

This work was partially supported by Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture of Japan, and by NIFS Collaboration Research Program.

References

[1] Y. Takamura et al., Plasma Fusion Res. 3 (2008) S1078.
[2] P. J. Clarricoats and A. D Olver, *Corrugated Horns for Microwave Antenna* (Peter Peregrinus, London, 1984).
[3] K. Ogura,et at., IEEJ Trans. FM, **127**, 681 (2007).
[4] K. Ogura,et at., J. Plasma Fusion Res. SERIES, **6**, 703 (2004).
[5] K. Ogura,et at., J. Plasma Phys., **72**, 905 (2006).
[6] K. Ogura,et at., Phys. Rev. E, **53**, 2726 (1996).
[7] K. Ogura,et at., J. Phys. Soc. Jpn., **67**, 3462 (1998).