Weakly Relativistic K-band Oversized Backward Wave Oscillator with Bragg Reflector at Input End of Slow Wave Structure

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Abstract

We report an oversized K-band backward wave oscillator (BWO) operating above 20 GHz in the weakly relativistic region less than 100 kV. It is very important to prevent microwave from going into the beam diode, since intense microwaves will harmfully affect beam generation. A weakly relativistic oversized BWO is demonstrated using a Bragg reflector at the input end of slow wave structure (SWS). The effect of the Bragg reflector on the BWO operation is examined, by changing the boundary condition at the SWS input end. The Bragg reflector improves the performance of the oversized BWO.

Introduction

Microwaves at moderate-power level or high-power level are demanded for widespread applications such as plasma heating, plasma diagnostics, telecommunication systems and radar systems. Slow-wave high-power microwave devices such as backward wave oscillator (BWO) can be driven by an axially injected electron beam without initial perpendicular velocity and has been studied extensively as a candidate for high power microwave sources [1]. In the slow-wave devices, a slow-wave structure (SWS) is used to reduce the phase velocity of electromagnetic wave to the beam velocity. To increase the power handling capability and/or the operating frequency, oversized SWSs have been used successfully [2-8]. The term "oversized" means that the diameter is larger than free-space wavelength λ of output electromagnetic wave by several times or more. The relativistic diffraction generator and multi-wave Cherenkov generator are special versions of the oversized BWO and have produced peak powers of GW level [2,3]. For these relativistic devices, the pulsed power and magnetic field systems are very large and heavy. For practical applications, operations at reduced voltage and at reduced magnetic field are preferable, since the systems become compact. However, the phase velocity of electromagnetic mode should be slowed down close to the beam velocity, ensuring enough beam coupling with electromagnetic modes. This issue becomes very difficult by reducing the beam voltage. In Ref. 6, the power level about 500 MW has been demonstrated at 8.3 GHz (X-band) at a moderate voltage of about 500 kV.

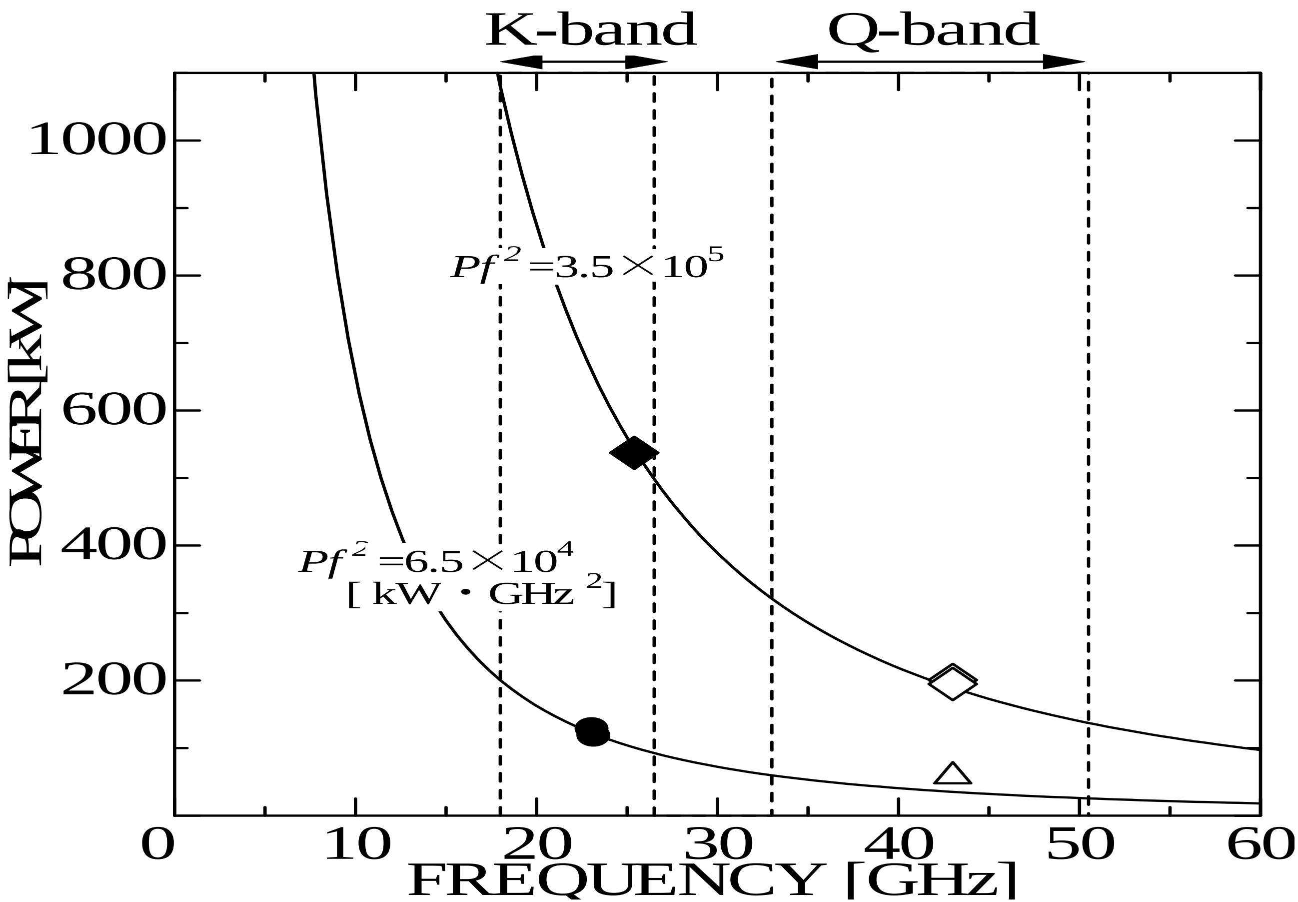
We study oversized BWOs operating in the relatively high frequency region, in K-band and Q-band [4,5,7,8]. Unique features of our BWOs are (1) they are driven by a weakly relativistic electron beam less than 100 kV, (2) the operation frequencies are relatively high, above 10 GHz and (3) the guiding magnetic field is relatively low, less than 1 T. Note that high-power operations beyond 10 GHz are difficult for the conventional non-oversized slow-wave devices. Recently, the performance of weakly relativistic oversized BWO has been improved. Radiation powers up to 500 kW (K-band) and up to 200 kW (Q-band) have been demonstrated in reference [9]. The quality factor *Pf* 2 of the weakly relativistic BWO has been improved up to about 3.5×105 [kW･GHz2].

Since beam generation will be harmfully affected by such intense microwaves, it is very important to prevent microwave from going into the beam diode region. In non-oversized devices, the beam input end of SWS can be terminated to a cut-off neck in order to reflect the microwave. For the oversized BWO, the electromagnetic field concentrates in the vicinity of SWS wall and the electron beam should be propagated within a few mm from the wall keeping its annular shape. The beam radius after cut-off neck becomes too small to operate efficiently. Other reflector than cut-off neck is required. A refractor such as mesh or inner metal plate at the beam input section is used to reflect microwaves [4-9].

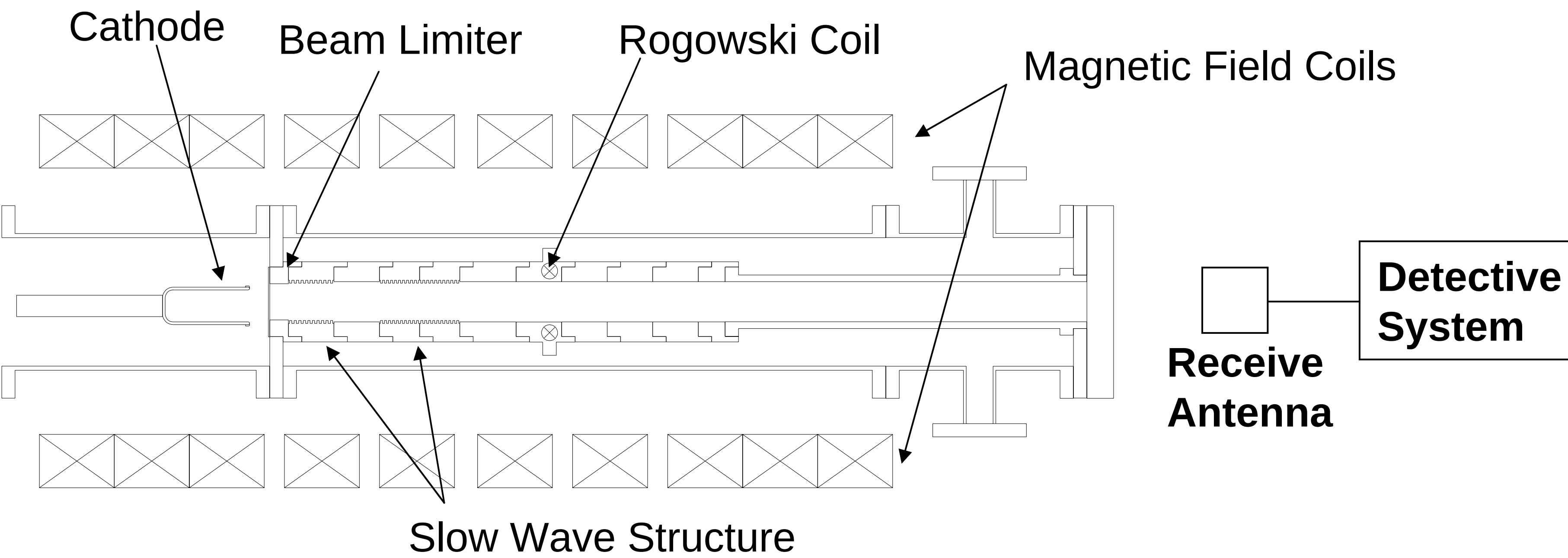
Beam interactions with such obstacles might generate plasma and cause a serious problem, so-called pulse shortening. Currently, this issue becomes very important problem and is studied extensively, see for example Chapter 4 of reference [1]. Moreover, obstacles at the SWS input may reduce the beam quality. By introducing beam energy spread and some non-uniformity of beam, the performance of the oversized BWO may be deteriorated. It is preferable to remove any obstacle from the beam path.

This work is aimed at studying a weakly relativistic oversized BWO with a Bragg reflector at the input end of SWS. The Bragg reflector reflects microwaves, while it is open for beam propagations. By changing the boundary condition at the beam entrance, the effect of the Bragg reflector on the BWO performance is examined.

Performance of weakly relativistic BWO
Beam voltage about 70 and 90 kV



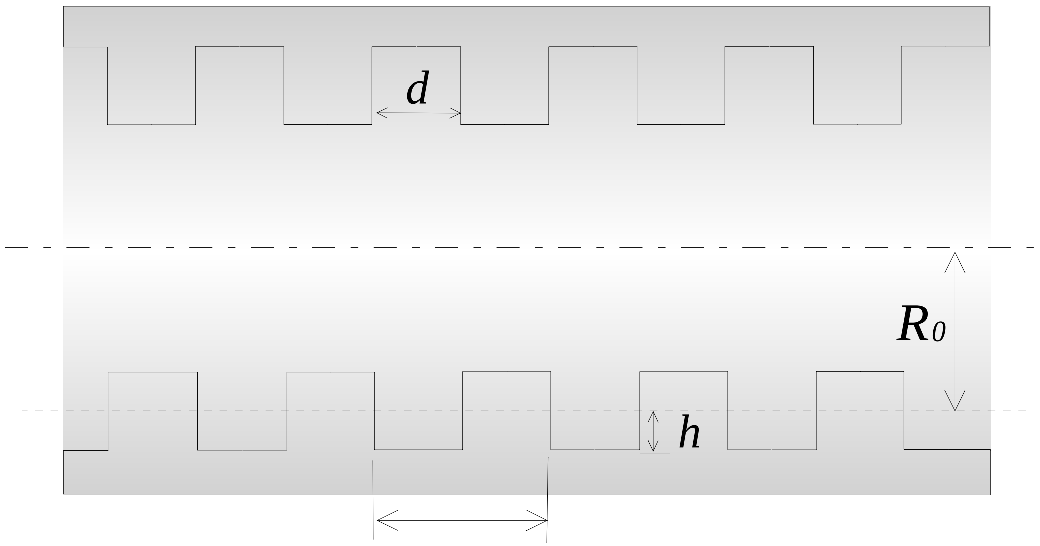
Experimental Setup



Cathode Voltage ≦100[kV]　Beam Current ≦0.5[kV]

A-K Gap：0～22[mm]　Magnetic Field：0.07～0.89[T]

Cylindrical Corrugated SWS



$Z_0 = 2\pi / k_0$

	R_0 [mm]	h [mm]	Z_0 [mm]	D/ λ
22GHz SWS	15.3	1.3	3.4	2.2
25.5GHz SWS	15.1	1.1	3.0	2.6

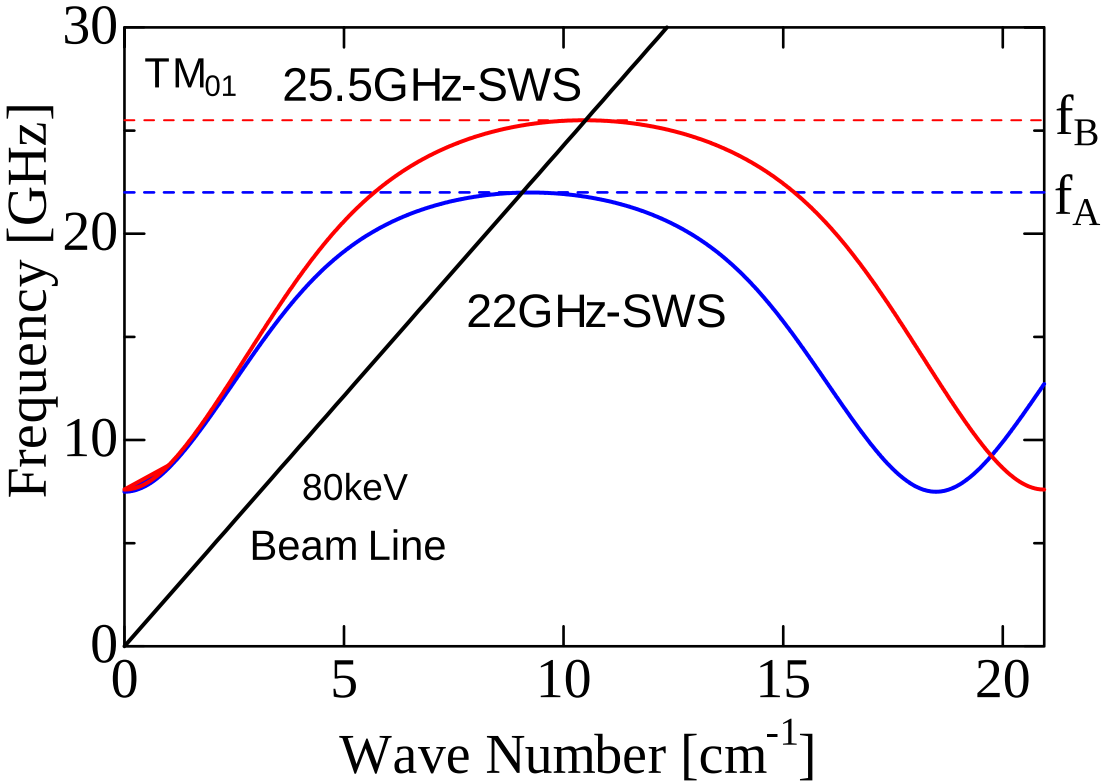
R_0 : **Average Radius** h : **Amplitude**

Z_0 : **Period** k_0 : **wave numbe**

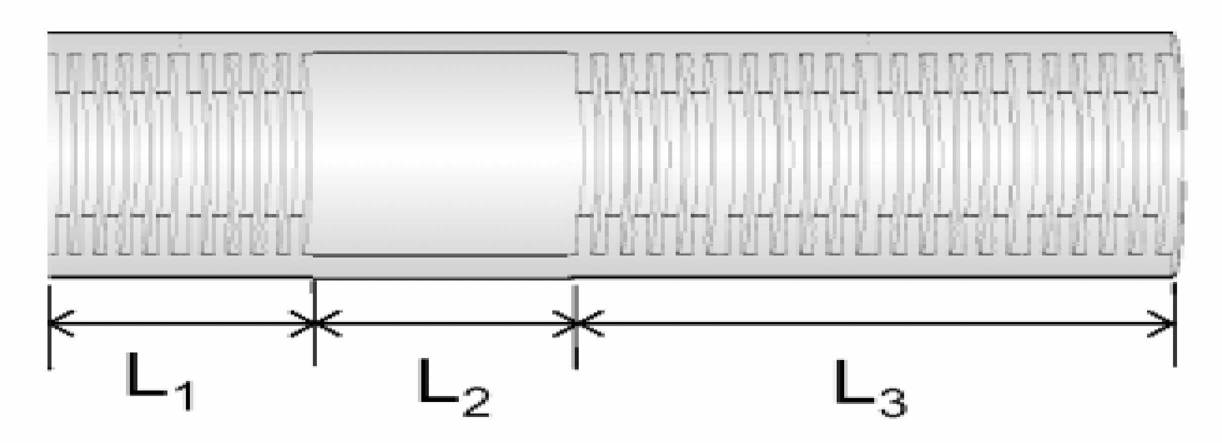
D : **Average Diameter**

λ : **Wave length of Output Radiation**

Dispersion curves of TM01 for periodic SWS listed in table 1. One has the upper cut-off frequency of *f*A=22 GHz and the other has *f*B=25.5 GHz.



Schematic of oversized BWO with a Bragg reflector



Starting Condition for Finite Length BWO

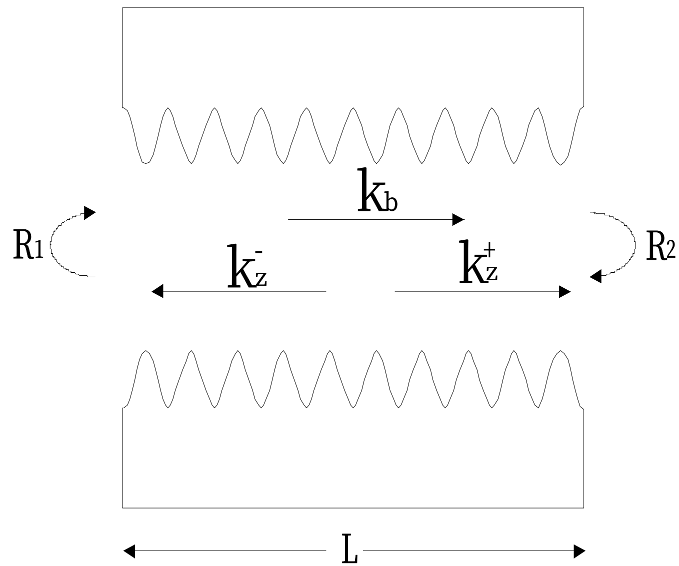
For a finite length BWO, the axial boundary condition is added due to the reflection at the both ends. The beam mode couples to and gives its energy to the backward electromagnetic mode. This interaction should satisfy the following equations simultaneously.

$D(f, k_b) = 0$ (P1)

$D(f, k_z^-) = 0$ (P2)

$R_1 R_2 \exp\{-i(k_z^- - k_b)L\} = 1$ (P3)

Here, and are respectively the wave number of backward electromagnetic and the beam mode, R_1 is the refraction coefficient at the beam entrance and R_2 is that at the other end. Equation (P3) comes from the requirement that the field must be a single value at any axial position, after one round trip of the field. In the limit of infinite *L*, k_z^- and k_b coincide and form a saddle point, resulting in the oscillation due to an absolute instability. For finite *L*, however, the oscillation will occur not at the saddle point.

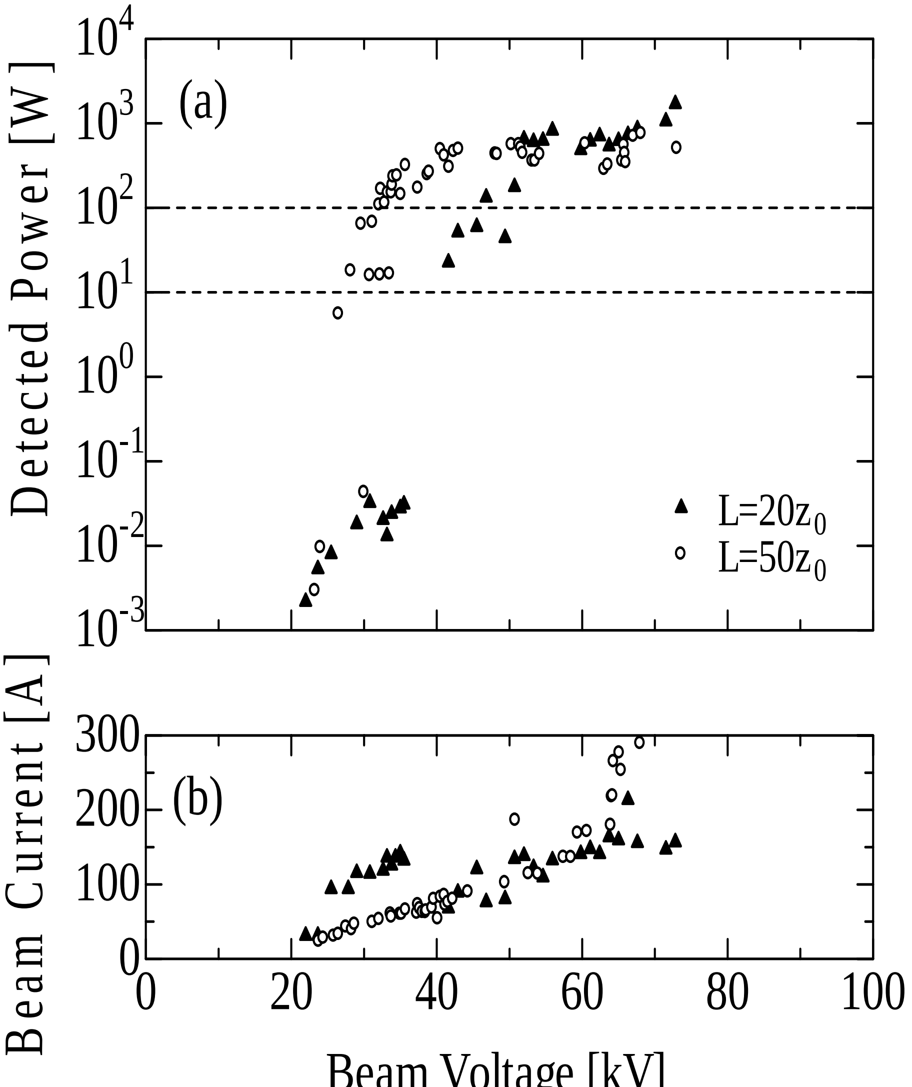


For the oscillation in the finite length BWO, two thresholds are imposed from the real and imaginary part of eq.(P3). The imaginary part mainly determines the starting current. The real part is

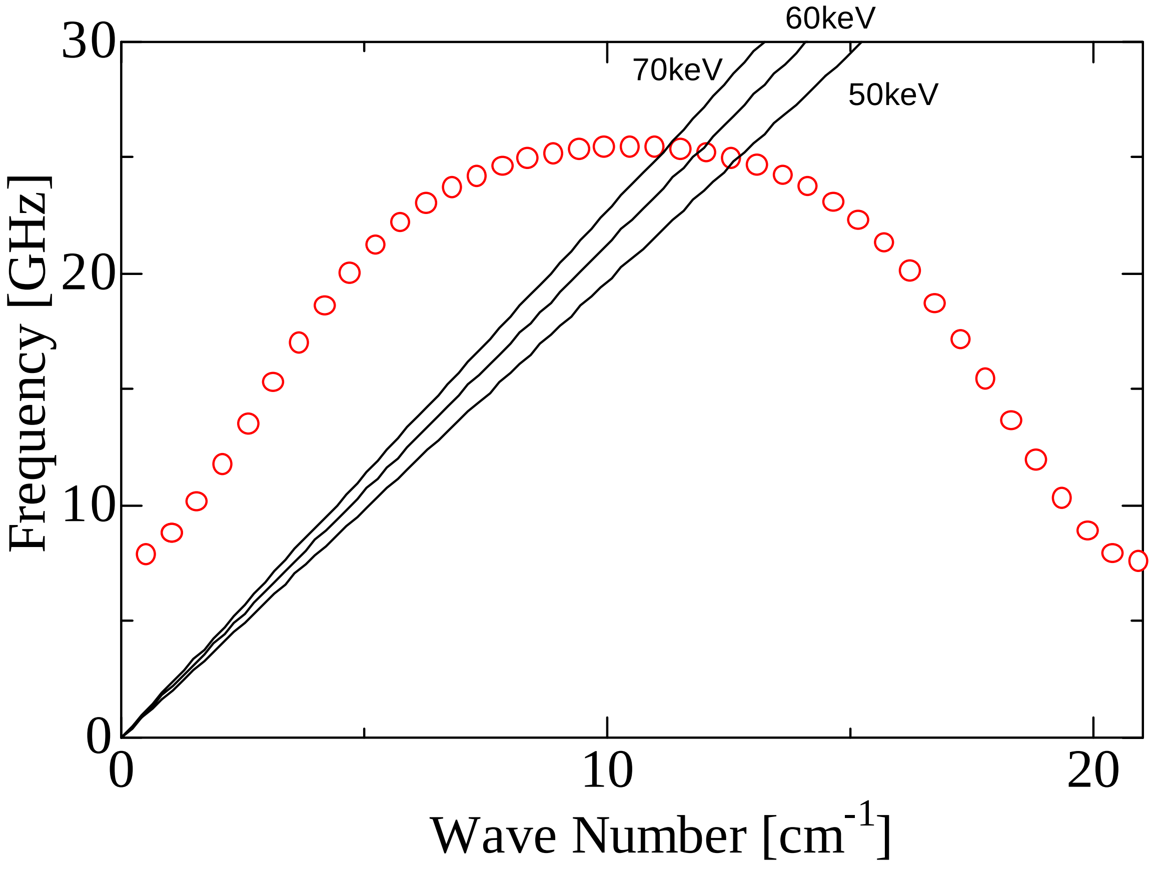
. $\mathrm{Re}(k_{z-}^{-} - k_b) = 2\pi N/L$ (P4)

Here, *N* is an integer corresponding to the spatial harmonic of the periodic system and *N*=-1 harmonic is dominant. To start an oscillation, the interaction width in the wave number space should be larger than $2\pi/L$. In the oversized BWO, this condition becomes critical and cannot be satisfied by increasing only the beam current. By increasing beam energy, the interaction point approaches the π point and Δk_z increases. At a critical beam energy (starting energy), Δk_z may become broad enough to satisfy eq.(P4).

There exists critical beam energy for oscillation.
(Starting Energy)

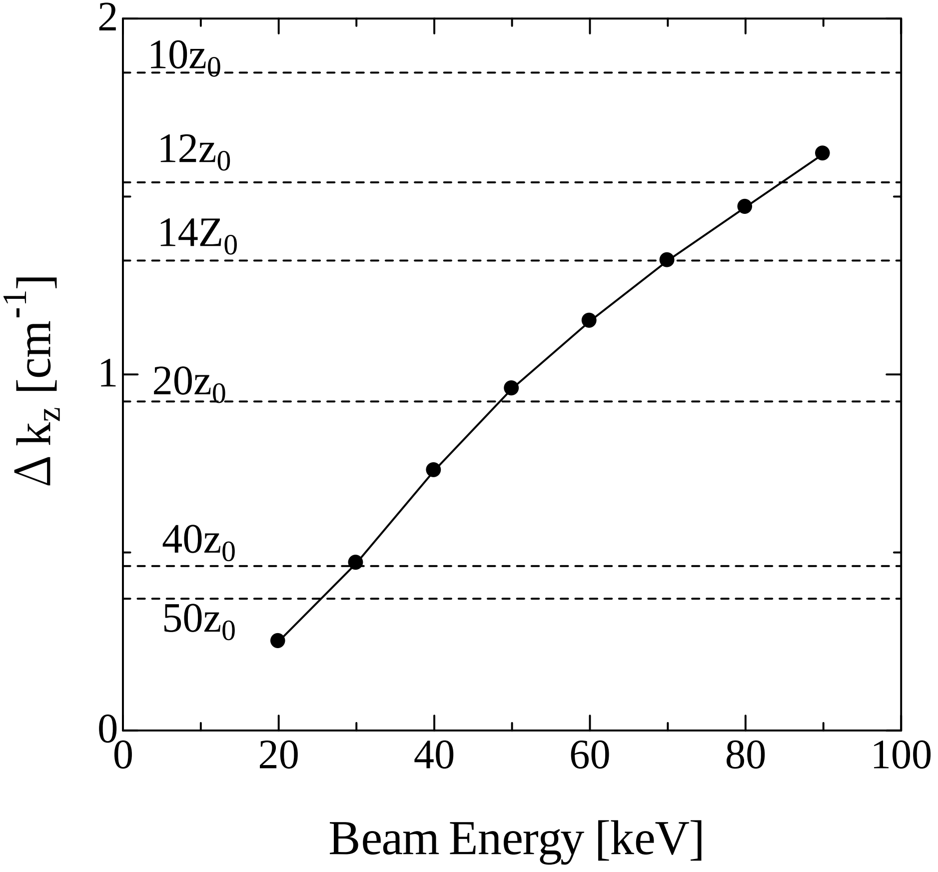


Axial Modes

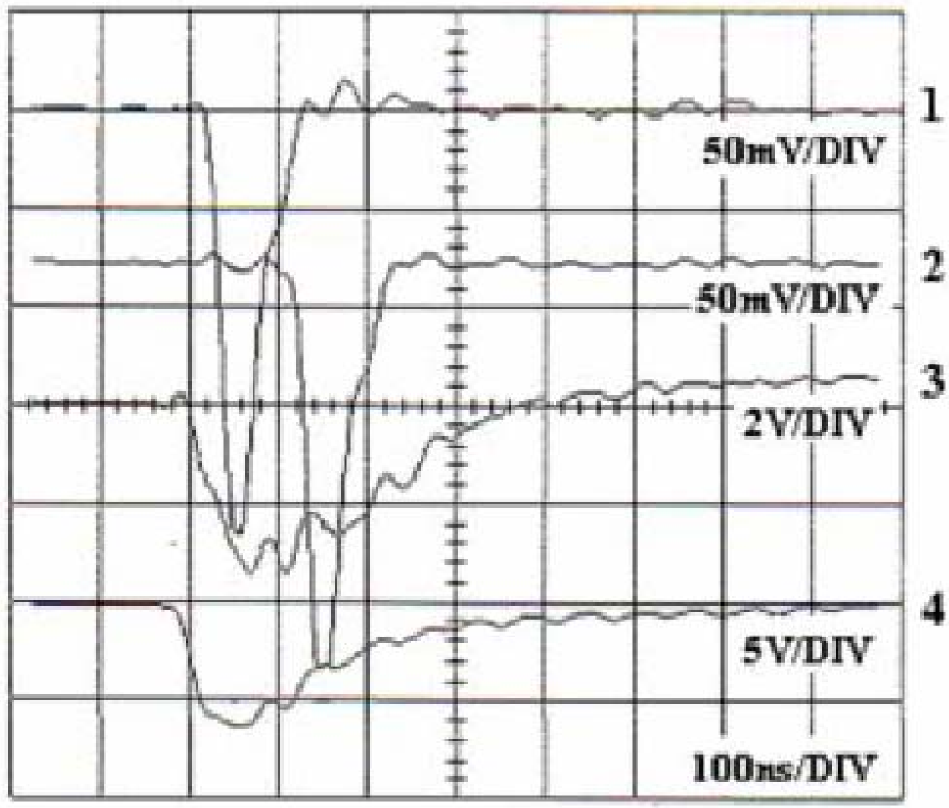


60keV
70keV
50keV
30
20
10
0
Frequency [GHz]
0
10
20
Wave Number [cm-1]

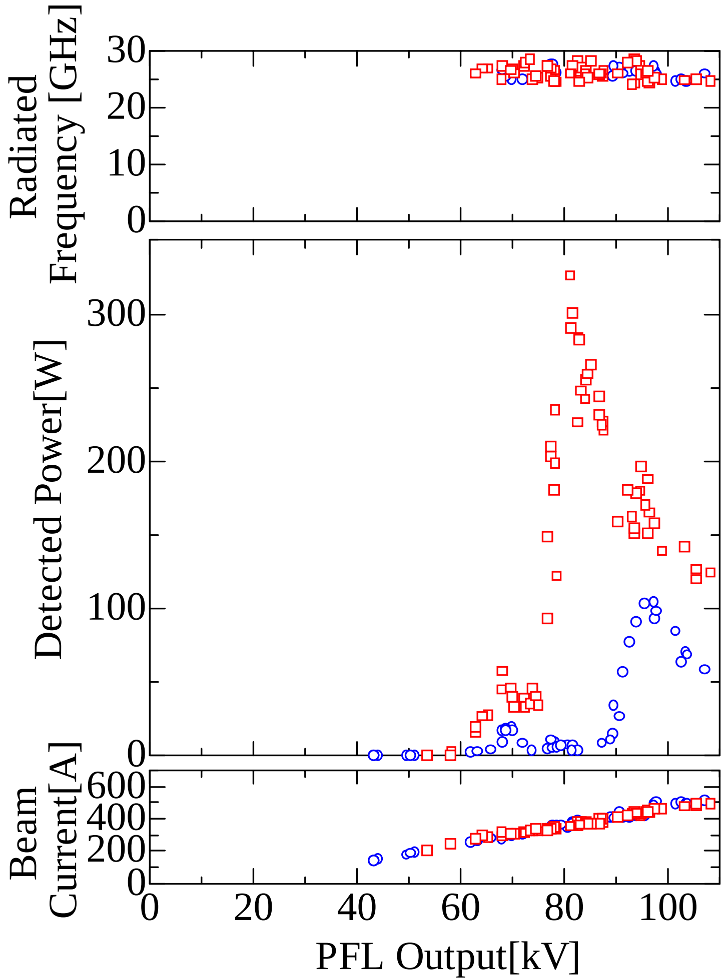
Numerically obtained interaction width Δk_z versus beam energy. Horizontal dashed lines are $2\pi/L$ for the SWS length L from $10z0$ to $50z0$



Waveforms of measured signal:1 prompt signal, 2 delayed signal, 3 beam current and 4 beam voltage

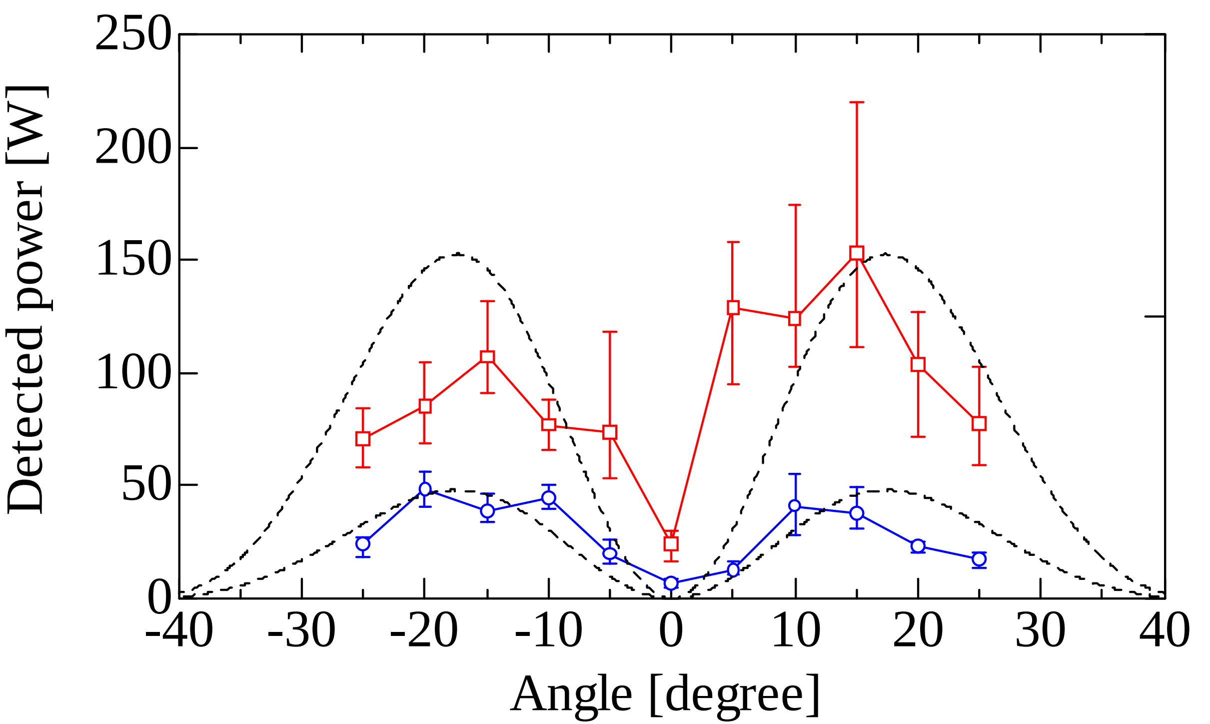


Weakly Relativistic Oversized BWO with Bragg Reflector

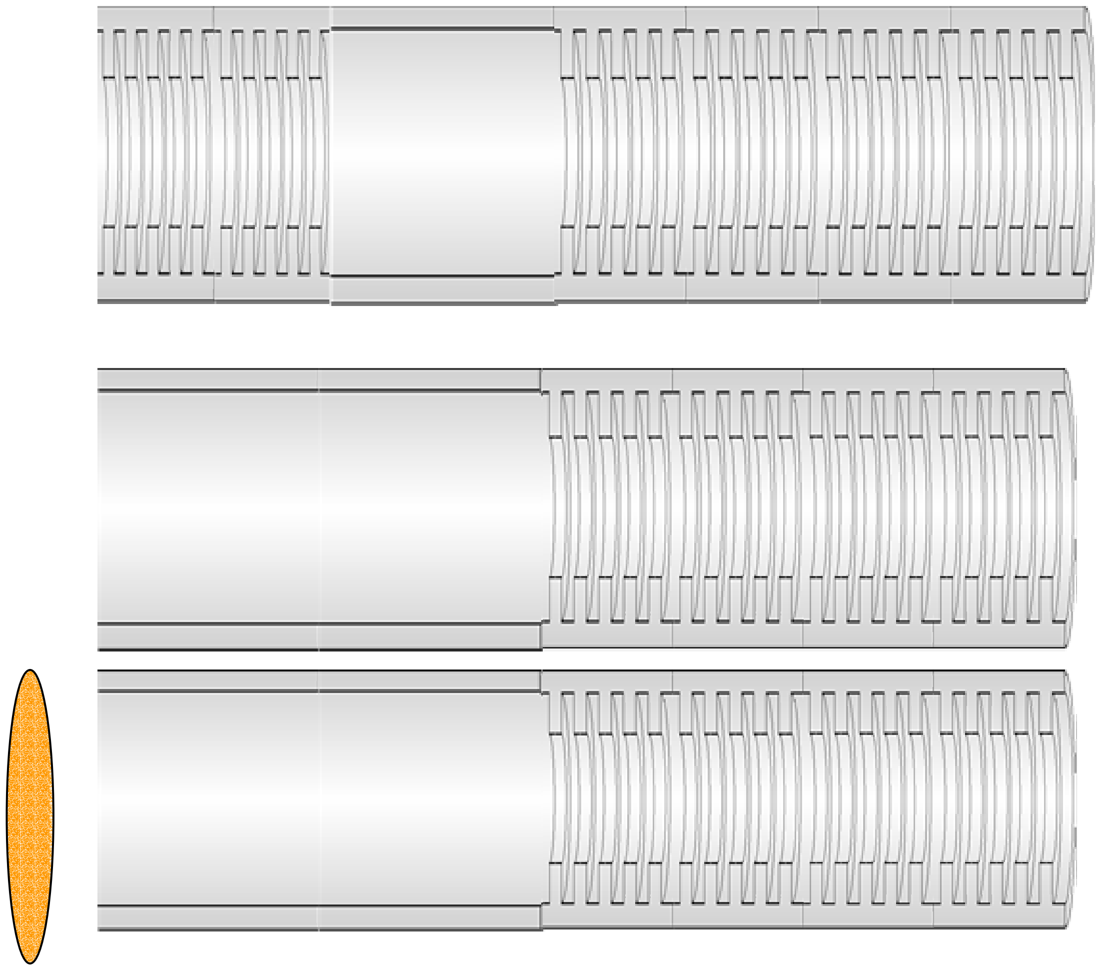


(□) for BWO with the Bragg refractor and (○) for BWO without the Bragg refractor.

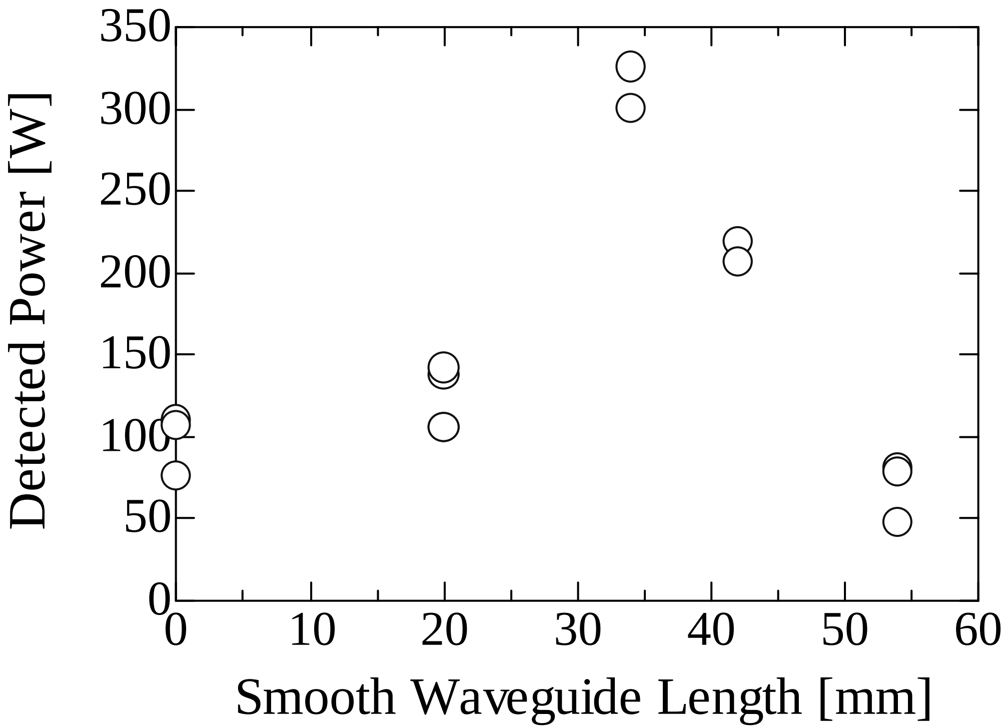
Radiation Pattern



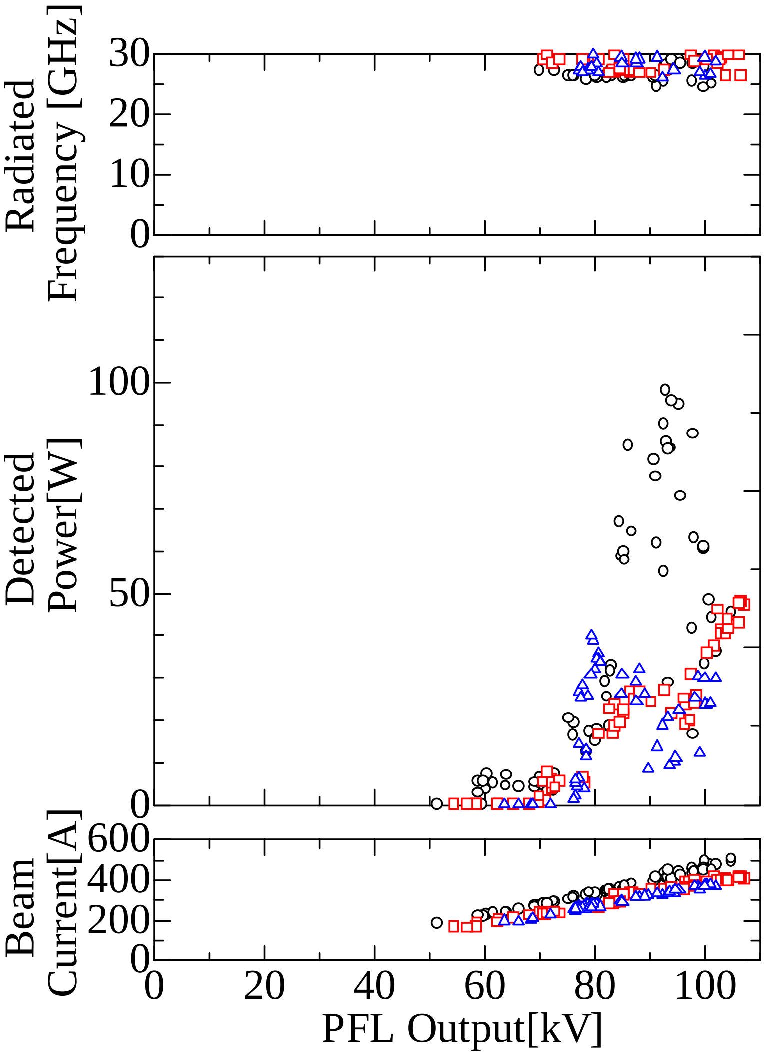
By changing the boundary condition at the beam entrance, the effect of the Bragg reflector on the BWO performance is examined.



Power dependence of the BWO with the Bragg refractor on the smooth waveguide length



Effects of SWS End



Beam input end is :(○) the 25.5 GHz SWS,(△) 34 mm smooth waveguide terminated by mesh and (◇) 68 mm smooth waveguide terminated by mesh.

Discussion and Conclusion

Oversized SWS can be used as a Bragg reflector, instead of mesh. Due to the change of end conditions, electromagnetic properties may be changed. The wave-beam interaction will be affected, since it depends on the field properties. In references [10,11], the effect of SWS end conditions on the non-oversized BWO operation has been studied. It has been shown that the electromagnetic field properties and the quality factors of axial mode are strongly affected by the end conditions. The efficiency and frequency agility of the non-oversized BWO can be improved by changing the end conditions [12]. However, the discussions are restricted in non-oversized BWOs, in which the electromagnetic fields are volumetric. In the case of oversized BWO, the field properties are quite different [6-9]. We show that the end conditions affect the BWO performance, even in the oversized case. And the oversized SWS can improve the performance of oversized BWO compared with the mesh reflector. The weakly relativistic oversized BWO with Bragg reflector at the input end of SWS is of considerable interest for practical use. In order to realize more efficient and stable oversized BWO using Bragg reflectors, the filed properties of operation mode and the beam coupling in the oversized SWS should be studied more definitely, considering realistic boundary conditions.