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Operation with a Quasioptical Antenna**

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## Abstract

High frequency gyrotron operation in the  $TE_{611}$  whispering gallery mode is reported. Powers as high as 112 kW and an efficiency as high as 25.4% have been obtained. In addition to the  $TE_{611}$  mode, ten other fundamental modes with frequencies between 133.9 GHz and 216.4 GHz were observed. A quasioptical antenna for whispering gallery modes has been tested for the  $TE_{611}$  mode. The combination of this antenna and a reflector produces a well collimated, linearly polarized rf beam suitable for electron cyclotron resonance heating or plasma diagnostics. The experimental conversion efficiency was determined to be 89%, and the cross polarization was down by 25dB. A new quasioptical transmission line employing this antenna has also been tested with the gyrotron. The absence of mode competition for the  $TE_{611}$  mode, as well as the efficient conversion of the output radiation into a linearly polarized Gaussian-like beam, substantiates the arguments for operation in surface modes in high power gyrotrons. The implications of quasioptical antennas for megawatt gyrotron window design are discussed.

## I. Introduction

Much progress in the development of high power high frequency gyrotrons has occurred over the past decade. This progress includes the development of CW gyrotrons capable of generating 200 kW at 28 GHz [1], 200 kW at 60 GHz [2], and 22 kW at 150 GHz [3]. Pulsed gyrotrons have generated powers in excess of 100 kW at 35 GHz [4], 45 GHz, 100 GHz [3], and 140 GHz [5].

The primary application for these gyrotrons is in the electron cyclotron resonance heating (ECRH) of fusion plasmas. The advantages of ECRH over other methods of plasma heating include the localized heating of the plasma, the simple launching structures required, and the possibility of locating the gyrotrons well away from the containment vessels. The recent ECRH experiments [6-8] have shown that the heating efficiency of ECRH is comparable to that of other heating techniques.

The development of high power high frequency gyrotrons is therefore of great importance. One problem associated with increasing the output power of gyrotrons is that of mode competition [9]. Higher output powers require larger cavities and higher order operating modes. Because the density of modes increases with cavity radius, the separation between the operating mode and competing modes decreases, and mode competition becomes a problem. This problem becomes particularly acute for the design of megawatt gyrotrons [10]. One promising class of modes for gyrotron operation is that of surface or “whispering gallery” modes [11,12]. Although a variety of nomenclatures are in use, surface modes can be defined as those  $TE_{mpq}$  modes for which  $(1 - m^2/\nu_{mp}^2) \ll 1$ , where  $\nu_{mp}$  is the  $p^{th}$  nonzero root of  $J'_m(x)$ . The modes in this class typically have a radial index  $p \sim 1$  or  $2$  and an azimuthal index of  $m \gg p$ . Because the output power is proportional to  $(\nu_{mp}^2 - m^2)/Q$ , and  $\nu_{mp} \sim m$  for surface modes, the use of a low diffractive

Q cavity may be necessary if high power CW operation is desired in surface modes [10]. The above definition of surface modes is qualitative. The value of  $m/\nu_{mp}$  varies from 0 to above 0.9 for modes of interest in gyrotron research. In the present discussion, modes with  $(1 - m^2/\nu_{mp}^2) \leq 0.5$  will be considered surface modes, while the remaining modes will be considered volume modes.

Surface modes are of interest in gyrotron research because they have low mode competition [12]. These modes are excited by placement of the electron beam near the cavity wall. Such a beam is less likely to excite nearby volume modes while other surface modes are generally spaced far apart. Placement of the electron beam near the wall also reduces voltage depression due to space charge. Gyrotrons with whispering gallery mode cavities have been successfully operated at 15 GHz [11], and operation at 140 GHz in whispering gallery modes has been suggested [12]. The operation of complex cavities in  $TE_{mp1} - TE_{m,p+1,1}$  pairs of whispering gallery modes has also been reported [13].

In this paper, we report the operation of a high power (110 kW) high frequency (143 GHz) gyrotron which operates in the  $TE_{611}$  whispering gallery mode. The design of the cavity and the operational characteristics of the gyrotron are presented. Results indicate that whispering gallery modes allow high efficiency single mode operation.

We also report results obtained with a mode transformer or quasioptical antenna which directly converts a whispering gallery mode into a polarized, collimated free-space beam. Such a mode transformer was originally discussed in Ref. [14]. The use of this quasioptical antenna significantly simplifies the transformation of a whispering gallery mode into a radiation pattern that is well suited for ECRH in plasmas. The generation of a collimated polarized beam is also important for gyrotrons which are designed for plasma diagnostics. The possibility of reducing the incident power density on the gyrotron output window by

placing the window in the far field of this radiating structure is also discussed.

This paper is organized as follows. In Section II, the design and operating characteristics of the  $TE_{611}$  gyrotron are discussed. Section III details the results obtained with the quasioptical antenna, including far field scans and conversion efficiency measurements. The implications of the whispering gallery mode results for the design of high power, high frequency gyrotrons are discussed in Section IV.

## II. Whispering Gallery Mode Experiment

The MIT gyrotron was originally designed for operation at 140 GHz in the  $TE_{031}$  volume mode with the electron beam at the second radial maximum of the cavity rf field [5,15]. The electron gun (Varian model VUW-8140a) produces an annular beam of 5A current at 65 kV. The pitch factor is  $v_{\perp}/v_{\parallel} = 1.5$ , and the pulse duration is  $1 - 2 \mu s$ . The electron gun has a laminar flow of electrons and typically operates with a magnetic compression ratio of about 25. The design of a whispering gallery mode cavity for use in the MIT gyrotron was thus constrained by these parameters and, in particular, by the beam radius.

The goals of the whispering gallery mode experiment were 1) 100 kW operation at approximately 140 GHz, and the demonstration of the 2) minimal mode competition and 3) adequate beam clearance when operating in whispering gallery modes. Pursuant to these goals, the whispering gallery modes considered were the  $TE_{511}$ ,  $TE_{611}$ , and  $TE_{711}$  modes. Each mode requires a different cavity radius in order to operate at 140 GHz. The  $TE_{511}$  mode was excluded because this radius is too small and the beam was too close to the cavity wall. For the  $TE_{711}$  mode the radius is too large, which yields poor beam coupling and potential competition from the  $TE_{131}$  mode. The  $TE_{611}$  mode exhibits strong beam coupling and is well isolated from other modes. The  $TE_{611}$  cavity was designed with  $0.5^{\circ}$  input and  $4^{\circ}$  output taper angles; the straight section length was  $3\lambda$ . The diffractive  $Q$ ,  $Q_D$ , was calculated to be 400 according to a code that simulates the rf field in the cavity [16]. The maximum theoretical efficiency,  $\eta_{T,max}$ , was 38% assuming a fixed Gaussian profile. The ohmic  $Q$  is calculated to be 4870, and the average wall loading is calculated to be  $4.6 \text{ kW/cm}^2$  for 100 kW of output power. The initial design constraints called for a wall loading  $P_w < 2 \text{ kW/cm}^2$ , however this value could not be achieved with this particular

electron gun because the electron beam radius is too small. However, the results presented in this paper should easily extrapolate to higher order surface modes that would satisfy the wall loading constraint.

Experimental results obtained with the  $TE_{611}$  mode at 143.06 GHz are shown in Fig.1. In order to achieve the optimum power and efficiency at each current, the magnetic field was adjusted to the value shown on the graph. The optimum magnetic field occurs at the low magnetic field side of the resonance band. The resonance band width was approximately 4.6% of the magnetic field. The power measurements were obtained with a modified Scientech, Inc. disk calorimeter discussed elsewhere [5]. The maximum efficiency of 25.4% occurred at a beam current of 3.7A; the maximum power of 112 kW was obtained with an 8.8A beam current. The starting current was measured to be 0.6A; the theoretical starting current is 0.54A. No beam interception was observed, even though the beam radius ( $R_e$ ) was comparable to the cavity wall radius ( $R_c$ ), with  $R_c - R_e \simeq 0.7 \pm 0.1$ mm.

The absence of any competing modes allowed the  $TE_{611}$  mode operation at the magnetic field detuning values necessary for peak efficiency at any given current. This is in contrast to gyrotron operation in higher order ( $n > 2$ ) symmetric  $TE_{0n}$  modes, for which mode competition from  $TE_{2n}$  modes on the low field side of the  $TE_{0n}$  excitation band prevents operation at the optimum magnetic field [5]. The ability to operate in modes which exhibit little or no mode competition has important implications for high power gyrotron design.

The discrepancy between the maximum efficiency of 25.4% and the theoretical maximum of 38% may result from several factors. The electron beam radius may be slightly smaller than the radius of the rf field maximum, resulting in a variation of the rf field across the beam. As a result of this the rf field could not be simultaneously optimized



for all electrons in the beam. A lower value of the  $v_{\perp}/v_{\parallel}$  ratio of the beam would also result in lowered efficiency. The ratio of the theoretical efficiency to the experimental efficiency is similar to that obtained for previous operation in volume modes with this electron gun. This suggests there is no reason unique to whispering gallery mode operation that is responsible for this discrepancy.

The  $TE_{611}$  mode was radiated into free space from the end of the circular output waveguide (radius  $R_w = 1.105$  cm). The far field radiation pattern is shown in Fig.2. The theoretical far field pattern is shown as a solid line. The close agreement between theory and experiment indicates there is little mode conversion occurring in the uptaper or output waveguide.

In addition to the  $TE_{611}$  mode, many other modes were also observed with this cavity. Table 1 lists the modes and the magnetic field values at which they were observed. Unless otherwise noted, the frequency measurements were made with a harmonic mixer system employing a surface acoustic wave dispersive delay line [17]. The maximum power obtained in each mode is shown, along with the corresponding efficiency associated with that power. The beam voltage for all of the data in Table 1 was approximately 65 kV. Frequency measurements were not carried out for the  $TE_{231}$  and higher field modes; the frequency and identification of these modes was inferred from the magnetic field value and known field values for the lower frequency modes. In excess of 50 kW was obtained in the  $TE_{331}$  mode at 216.4 GHz. At this field, the electron gun is operating at a compression ratio of 36. As is apparent from Table 1, the best beam-field coupling occurred for the  $TE_{321}$ ,  $TE_{421}$ , and  $TE_{521}$  modes. These modes are very similar to the  $TE_{m11}$  whispering gallery modes and have fields which are well coupled to beams with large radii. In contrast, the  $TE_{m11}$  modes with  $m > 6$  begin to decouple from the beam as  $m$  increases; the single

radial maximum in the rf field moves closer to the wall.

Second harmonic emission was not observed with this cavity, in spite of careful attempts to locate harmonics. The most plausible explanations may be the low  $Q$  of  $TE_{611}$  cavity and the relatively low  $v_{\perp}/v_{\parallel}$  of 1.5 for this electron gun. In previous second harmonic studies on the MIT gyrotron with a  $TE_{031}$  cavity and a nonlaminar electron gun, many second harmonic modes were observed [18]. However, the  $TE_{031}$  cavity had a total  $Q$  of 1300, and the electron beam produced by the nonlaminar electron gun probably had a  $v_{\perp}/v_{\parallel}$  ratio of closer to 2.0. With the appropriate  $Q$  and  $v_{\perp}/v_{\parallel}$ , the operation of second harmonic gyrotrons in whispering gallery modes is not only feasible, but also desirable because of the reduced mode competition.

The results reported here confirm the absence of mode competition and the corresponding accessibility of the high efficiency zone of operation for whispering gallery modes. In the case of the  $TE_{611}$  mode, the primary competing mode is the  $TE_{021}$  mode, which is excited between 51.5 and 53.8 kG at 4A. This is well below the optimum magnetic field of 55.8 kG for the  $TE_{611}$  mode. Location of the electron beam close to the wall also reduces voltage depression of the beam, which could be especially severe at high currents.

### III. Quasioptical Antenna Experiment

In designing high power high frequency gyrotrons for ECRH and plasma diagnostics, it is usually necessary to produce a well collimated linearly polarized beam of radiation. For gyrotrons operating in  $TE_{0n}$  modes, the power produced in the  $TE_{0n}$  mode is usually converted by a series of mode converters based on perturbations of the walls of the output waveguide [19]. The first section converts the  $TE_{0n}$  mode into the  $TE_{01}$  mode. The  $TE_{01}$  mode is then converted to the  $TE_{11}$  mode, which is sometimes converted to the  $HE_{11}$  mode. This mode upon launching produces a near gaussian beam. Alternative mode conversion techniques for  $TE_{0n}$  modes include quasioptical transformers [20].

The decided advantage of operating gyrotrons in whispering gallery modes necessitates the development of a mode transformer which can produce a collimated linearly-polarized rf beam from the output radiation. A simple quasioptical mode transformer which accomplishes this transformation in one step has been studied by Vlasov et al. [14]. Such a transformer is basically an overmoded waveguide slot radiator.

Whispering gallery modes, as with other asymmetric modes in circular cavities with axial symmetry, are known to rotate. The electron beam-field coupling factor is proportional to  $J_{m\pm n}(k_{\perp} R_e)$ , where  $J_m$  is the Bessel function of order  $m$  and  $n$  is the harmonic number. The plus and minus signs correspond to the two rotations. For surface modes with radial index  $p = 1$ ,  $J_{m-n} > J_{m+n}$  for  $R_e < R_0$ , the cavity radius, and only the rotation corresponding to the  $J_{m-n}$  coupling coefficient is excited. This rotation occurs in the same direction as the electron cyclotron motion. Furthermore, the fields of whispering gallery modes are well localized near the waveguide wall, and the electric field is almost entirely in the radial direction. Consequently, the whispering gallery mode may be modeled by a set of plane waves which skim along the wall as they propagate down the

waveguide [21]. These plane waves propagate in a helical path with the rotation sense of the whispering gallery mode and the pitch angle given by  $\theta_B = \sin^{-1}(k_{\perp}/k)$ . If a straight axial cut is made in the waveguide (see Fig. 3a), the plane waves will be radiated into space at this edge. The second cut is a helical cut at pitch angle  $\theta_B$ , which proceeds a full  $360^\circ$  around the waveguide and intersects the straight cut. This helical cut is the path taken by one of the plane waves. Because the fields actually have a finite distribution at the wall, the inner caustic is less than the cavity radius, and the waves are radiated over a range of angles (see Fig. 3b). Within the approximations of geometrical optics, the angular width in the plane  $z = 0$  is  $2\alpha_{mp}$  where  $\alpha_{mp} = \cos^{-1}(m/\nu_{mp})$ .

The cylindrical wave can then be converted into a collimated, polarized ( $\mathbf{E} = E\hat{y}$ ) beam by means of a cylindrical reflector of parabolic cross section. The focal line of the reflector is colinear with the straight cut edge of the quasioptical antenna. The width of the beam produced by the reflector in the x-y plane (Fig. 3b) is given by

$$4F \left[ \frac{(\nu_{mp} - m)}{(\nu_{mp} + m)} \right]^{\frac{1}{2}}$$

where  $F$  is the focal length of the reflector. A more detailed treatment which includes diffraction effects can be derived by rigorously decomposing the waveguide TE wave into planewaves [14].

A quasioptical antenna for the  $TE_{611}$  mode has been constructed and tested with the 143 GHz gyrotron described in the previous section. The output waveguide diameter is 2.21 cm and the bounce angle is  $\theta_B = 13.1^\circ$ . The length of the straight cut is thus 29.84 cm. Antennas of both rotation senses were constructed. A parabolic reflector was unavailable; a cylindrical reflector with a circular cross section was constructed from a section of 22.9 cm diameter waveguide. For the angular width of the beam, this reflector closely approximates a parabola. The focal length of the reflector was 5.72 cm. After

laser alignment of the reflector and the antenna the radiation pattern was measured with a calibrated attenuator and diode. A two dimensional scan of power in the y-polarization was performed in the  $x' - y$  plane (see Fig. 3a) normal to the beam propagation direction. A contour plot of the radiation pattern for this polarization is shown in Fig. 4. The beam is seen to be well collimated. The theoretical pattern dimensions based on geometrical optics are a height ( $y$ ) of 7.62 cm and a width ( $x'$ ) of 6.73 cm. A 2-dimensional scan for the orthogonal polarization  $\mathbf{E} = E\hat{x}'$  confirmed the highly polarized nature of the beam; power in the orthogonal polarization was at least -25dB below the peak power for the correct polarization.

An estimate of the conversion efficiency for the antenna-reflector combination was obtained using the disk calorimeter described previously. The calorimeter was centered at the position corresponding to the maximum of the beam and the power was measured. The antenna was then removed from the end of the output waveguide and the power radiated from the end of the pipe was again measured. An estimate of the conversion efficiency was obtained from the ratio of these two powers and is  $82 \pm 4\%$ . This is a lower bound on the conversion efficiency because the calorimeter has an active area only 10.16 cm in diameter. With the calorimeter centered at the pattern maximum, a significant amount (approximately 7%) of the power in the pattern missed the calorimeter.

Rotation of the  $TE_{611}$  mode was confirmed not only by the proper operation of the quasioptical antenna, but also by the improper operation of the same antenna when the magnetic field direction was reversed. The rf field rotates in the same direction as the electrons for the case corresponding to the  $J_{m-n}$  coupling. Thus the rotation sense of the helical cut on the antenna must be the same as the electron rotation direction. After initial operation in the correct rotation, the magnetic field direction was reversed. No other

operating parameters were changed. The rf field was then rotating in the opposite direction. The radiation pattern produced was no longer well collimated; power was radiated into a very large solid angle. The correct antenna for this rotation was then substituted, and the radiation pattern was again that of a well collimated, polarized beam.

A quasioptical transmission line employing this antenna was also tested; the configuration is shown in Fig. 5. The shear line or straight cut of the antenna was placed at the center of a 22.86 cm diameter 2 m long waveguide. The beam is then focussed to a line each time it intersects the waveguide axis as it reflects down the walls of the waveguide. After many reflections, two in this case, the beam exits the pipe and is collimated by a reflector with focal line colinear with the waveguide axis. The two dimensional radiation pattern was then measured in the plane  $(x' - y)$  normal to the beam direction. The pattern was virtually indistinguishable from that of Fig. 4; power in the opposite polarization remained at least -16dB below the correct polarization. Such a quasioptical transmission line could have important applications for rf transmission from the gyrotron to the plasma.

#### IV. Discussion and Conclusions

The operating characteristics of a high frequency (143 GHz)  $TE_{611}$  whispering gallery mode gyrotron have been presented. Output powers as high as 112 kW and an efficiency as high as 25.4% have been obtained. Operation of the  $TE_{611}$  mode has demonstrated the absence of mode competition problems associated with operation in other volume cavity modes. The absence of electron beam interception in spite of the proximity of the beam to the wall has been demonstrated. These results substantiate the arguments for operation in whispering gallery modes in megawatt power level gyrotrons. The reduction in mode competition and the lower voltage depression of the electron beam for larger  $R_e/R_0$  will allow operation in highly overmoded, large diameter cavities.

In addition to the  $TE_{611}$  mode, ten other modes with frequencies of 133.9 GHz to 216.4 GHz were observed. In particular, 90 kW with 25% efficiency at 176.5 GHz was observed in the  $TE_{421}$  mode, and 52 kW with 18% efficiency at 216.4 GHz was observed in the  $TE_{331}$  mode. For the  $TE_{331}$  mode, the electron gun operated at a compression ratio of 36.

A quasioptical antenna for the  $TE_{611}$  mode has been constructed and tested. This antenna in combination with a reflector produces a well collimated, linearly polarized rf beam. Such an antenna is useful for the straightforward conversion of high power high frequency gyrotron radiation to a collimated beam appropriate for either ECRH in fusion plasmas or plasma diagnostics. Use of the quasioptical antenna in a reciprocal arrangement could allow the injection of power into waveguide whispering gallery modes. Such a configuration is useful for injection locking oscillators or gyroklystron or gyrotwyston amplifiers. This quasioptical antenna also has the advantage of operating equally well for any surface mode generated in the same cavity. Although the angular width ( $\alpha_{mp}$ ) of

the radiation pattern depends on the operating mode, both the pitch and length of the antenna itself depend only on the relative diameters of the cavity and output waveguide. Consequently, this quasioptical antenna could be used with a gyrotron which is step tuned in frequency from one surface mode to another. Such a system could have important applications in plasma heating.

Operation in whispering gallery modes with this quasioptical antenna may prove to be a solution to the difficult problem of window design for megawatt power level gyrotrons. The antenna and a reflector could be located inside the vacuum chamber. The rf would be converted to a polarized, collimated, large area beam which could then be passed through a large area window. The resulting intensity incident on the window would be much lower than that for conventional waveguide windows. The window could also be mounted at Brewster's angle for zero reflection. An added benefit is the natural separation of the rf from the electron beam, allowing for a much larger collector capable of dissipating the remaining beam power or a depressed collector for energy recovery from the beam. One possible collector configuration is that of Fig. 5 where the large diameter pipe serves as the collector.

The demonstration of a simple quasioptical transmission line employing the antenna structure has also been reported. The high collimation and polarization of the rf beam were maintained over a 2 m distance. Such a transmission line is easily scalable to larger dimensions and could prove useful for power transmission in electron cyclotron resonance heating systems.



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## FIGURE CAPTIONS

Fig. 1 Operating characteristics for the  $TE_{611}$  whispering gallery mode gyrotron.

Fig. 2 Angular far-field scan of  $TE_{611}$  whispering gallery mode radiated from end of circular waveguide. Circles denote positive angles and triangles denote negative angles. Theoretical pattern is shown as a solid line.

Fig. 3 a) Side view of quasioptical antenna and reflector for whispering gallery mode gyrotron. b) End view of quasioptical antenna and reflector.

Fig. 4 Two-dimensional far-field scan of rf beam produced by quasioptical antenna and reflector. The 3, 6, 10, and 20 dB contours are shown.

Fig. 5 Transmission line employing quasioptical antenna and reflector.

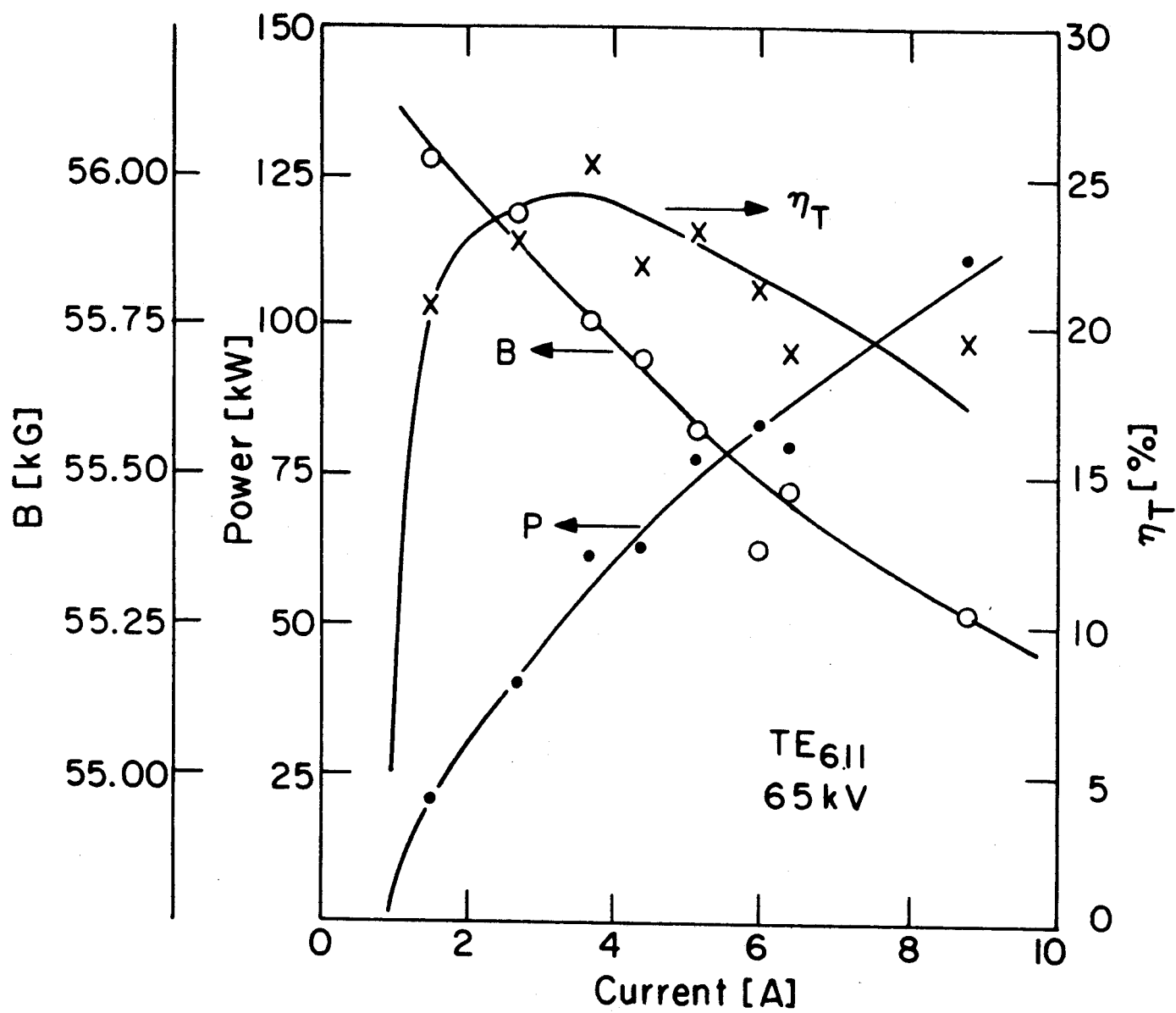


Fig.1

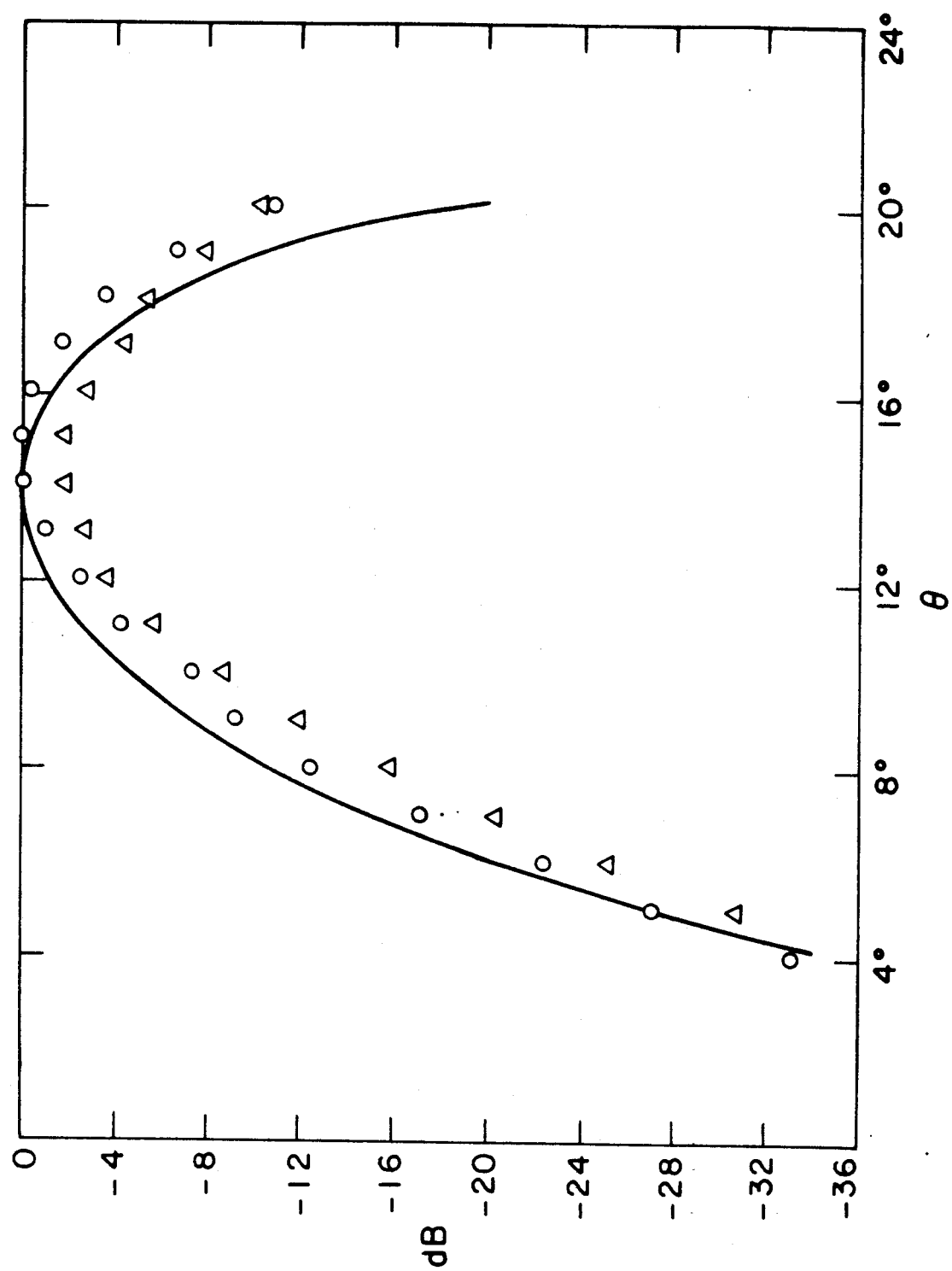


Fig.2

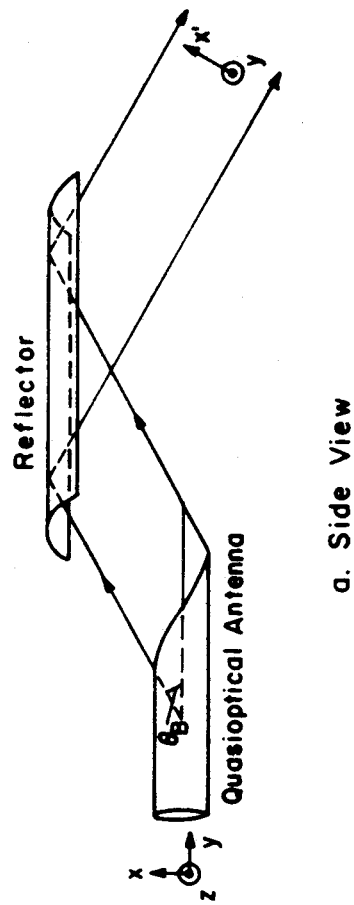
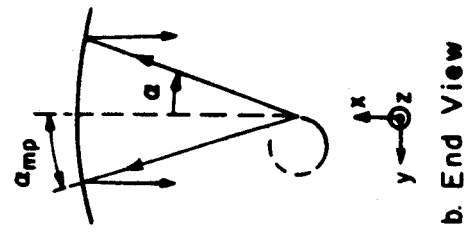


Fig.3



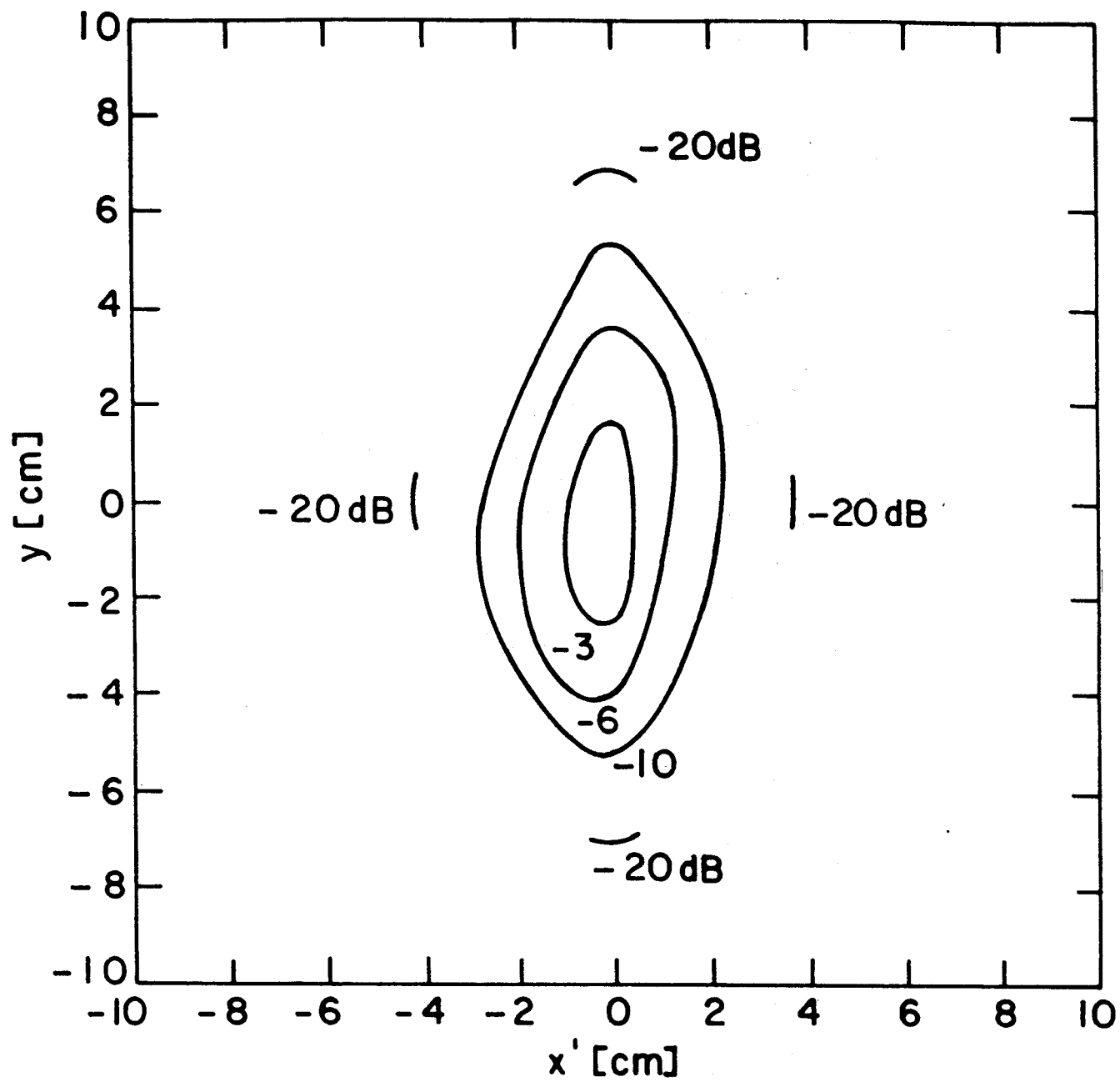


Fig.4

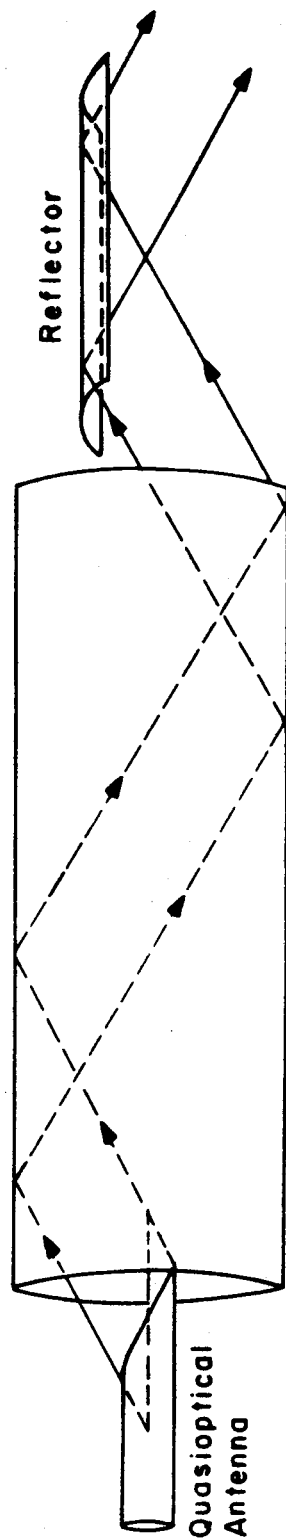


Fig.5

**Table 1**  
**Modes Observed with Whispering Gallery Mode Cavity**

Mode	B[kG]	$\nu$ [GHz]	$P_{max}$ [kW]	$\eta$ [%] at $P_{max}$
TE <sub>021</sub>	52.35	133.9	42.7	11.2
TE <sub>611</sub>	55.27	143.1	112.0	19.5
TE <sub>321</sub>	59.32	152.5	77.9	20.3
TE <sub>711</sub>	63.44	164.0	57.1	17.6
TE <sub>421</sub>	67.88	176.5	89.5	25.2
TE <sub>811</sub>	72.17	183.6	31.4	8.8
TE <sub>231</sub>	74.22	190.2	64.4	18.6
TE <sub>031</sub>	75.78	194.1	22.9	7.0
TE <sub>521</sub>	78.50	200.7	61.8	20.0
TE <sub>911</sub>	79.88	204.3	24.9	7.7
TE <sub>331</sub>	84.65	216.4	51.5	18.2