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ABSTRACT

In this paper, the prospects for electron cyclotron resonance heating (ECRH) and high power, high frequency gyrotrons are examined. Recent experimental and theoretical progess at MIT on the development of gyromontrons and gyroklystrons is described. It is shown that cw gyrotrons capable of MW powers and high efficiency are consistent with the technological constraints of the device. The design parameters of 1 and 10 MW, 120 GHz monotrons are given. An ECRH system based on such rf sources is described and compared with alternative plasma heating techniques.

INTRODUCTION

A number of highly successful ECR heating experiments have recently been carried out, including major efforts at GA Technologies (Prater and co-workers, 1984), Princeton (Hsuan and co-workers, 1984), and at the Kurchatov Institute in Moscow (Alikaev and co-workers, 1983). Gyrotrons have been used to generate 1 MW at GA and Kurchatov. These experiments have shown that the efficiency of coupling ECR power to the plasma is comparable to that of other heating techniques. ECRH is also attractive because the power can be locally deposited in the plasma. Therefore it can be used for profile control, which could result in operation at a higher plasma beta. In addition, gyrotrons do not require complex antennae and launching structures inherent with lower frequency rf techniques, or the necessity of being directly adjacent to the machine as required by neutral beams. By using ECRH in conjunction with an ion heating system, such as neutral beams, a more balanced heating process would be possible, which could improve the stability of the plasma. At present, it appears that future progress in ECRH will depend more on the availability and cost of high power gyrotrons than on the physics of the heating process itself.

Over the past decade both the frequency and the output power of gyrotron oscillators have increased rapidly. Earlier results include cw devices that have generated powers ranging from 200 kW at 28 GHz (Jory and co-workers, 1980) to 22 kW at 150 GHz (Andronov and co-workers, 1978). Gyrotrons are presently generating 100-200 kW in long pulse or cw operation at frequencies between 60 and 90 GHz (Felch and co-workers, 1984; Flyagin and co-workers, 1982). In addition, short pulse gyrotrons have produced powers in excess of 100 kW at 35 GHz (Carmel and co-workers, 1983), 45 GHz, 100 GHz, and 120 to 160 GHz (Kreischer and co-workers, 1984a). This progress has increased the possibility of producing competitive rf sources suitable for ECRH of fusion plasmas.

The bulk heating requirements of present tokamak experiments and proposed upgrades are between 10 and 50 MW, and frequencies in excess of 100 GHz will be required to heat plasmas confined by magnetic fields above 3.5 T. At present, high frequency gyrotrons have a relatively high cost per kW, and only operate cw at low powers, which makes a 10-50 MW ECR heating system based on such sources unattractive. Gyrotrons capable of powers greater than 1 MW could dramatically reduce the cost and complexity of an ECRH system. In this paper, we review past high frequency results at MIT, and examine the possibility of building such gyrotrons. Our analysis indicates that such powers can be achieved with both high efficiency and low ohmic losses. Although some problems, such as mode competition, will require further research, megawatt gyrotrons, if successfully built, could compete very favorably in cost, efficiency, simplicity, and reliability with other heating sources.

OPERATION AT 100 KW

High power testing of the MIT gyrotron was initiated in 1982 and the goal of 100 kW, 140 GHz operation in a single mode ($TE_{0,3,1}$) was achieved shortly thereafter. A detailed description of the design and initial operation of this experiment is given by Temkin and co-workers (1982). Since these early successes, the gyrotron has been operated over a wide range of parameters, and a broad spectrum of fundamental (128 - 162 GHz) and second harmonic (209 - 303 GHz) TE cavity modes have been excited. Initially, relatively low efficiencies were obtained (e.g., 17% at 100 kW operation in the $TE_{0,3,1}$ mode). As a result of a variety of modifications made to the experiment and diagnostics, and optimization of the operation of the device, both the output power and efficiency were increased to the levels predicted by theory.

Figure 1 indicates how the efficiency and power typically vary in a gyrotron oscillator as the beam current is increased. At each current the magnetic field has been optimized to produce the maximum power. No power is generated below the starting current, and above this current the efficiency quickly increases to a maximum value. For the MIT experiment a starting current of 0.2 A was measured, and the efficiency peaked at about 4-5 A. At higher currents the rf fields within the cavity become too large, and power is transferred back to the beam, causing a reduction in the efficiency. At MIT, 138 kW was generated in the $TE_{0,3,1}$ mode (140 GHz) and 175 kW was produced in the $TE_{2,3,1}$ mode (137 GHz). These represent total efficiencies of 24% and 30% respectively. The peak efficiency was 36% for the $TE_{2,3,1}$ mode, and 29% was obtained in the $TE_{0,3,1}$ mode. It is likely that the $TE_{0,3,1}$ could not reach higher efficiencies because of strong mode competition from the $TE_{2,3,1}$ mode, which prevented operation at the optimum magnetic field. In general, the best efficiencies were obtained with isolated, asymmetric modes ($TE_{m,p,q}$, m>0) at beam currents of 4-5A. This includes not only the $TE_{2,3,1}$ mode, but also the $TE_{4,2,1}$ (127 GHz) with a maximum efficiency of 33% and the $TE_{3,3,1}$ mode (156 GHz) with a maximum efficiency of 26%. Output powers exceeding 120 kW were also achieved in both the $TE_{4,2,1}$ and $TE_{3,3,1}$ modes. A comparison between these experimental results and theory indicates good agreement. For example, the measured efficiencies of isolated modes are close to predictions based on nonlinear theory.

A variety of sensitive diagnostics were developed in order to measure power, frequency and mode content. Power measurements were made with a Scientech calorimeter modified to greatly increase its absorptivity at millimeter wavelengths (Blaney, 1980). It was isolated from the transmission system in order to minimize feedback. The relatively small scatter in the data in Fig. 1 is a good indication that this system is quite accurate. Another technique that proved quite valuable for identifying mode conversion in the gyrotron was the measurement of far field patterns with a video diode. The amount of conversion in the transmission system could be determined by comparing observed patterns with those of pure modes. An example is shown in Fig. 2 for the $TE_{0,3,1}$ mode. The data was taken by scanning in a plane containing the output waveguide axis and measuring the power in the out-of-plane component of the rf field. The angle is measured with respect to the waveguide axis. The agreement between the data and theory is very good, and the small signals between the lobes is indicative of minimal mode conversion.

A harmonic mixer system was developed to measure the operating frequency of the MIT gyrotron to high accuracy (Kreischer and co-workers, 1984b). Using this diagnostic, bandwidths as low as 3 MHz, which is the instrumental limit, were observed at both low and high power operation. In addition, the gyrotron exhibited good shot to shot reproducibility. It is believed that the bandwidth is due to the $\pm 0.5\%$ ripple on the cathode voltage. The dependence of frequency on cathode voltage, magnetic field, and beam current was also measured. An example of such a measurement is shown in Fig. 3. It was found that, for a given current, the frequency shift due to voltage and magnetic field changes is due to their effect on the cyclotron frequency. The total shifts measured were on the order of ω/Q_D, where Q_D is the cavity diffractive Q. A comparison was made between low current experimental data and predicted frequency shifts based on linear theory. It was hoped that this comparison would provide information about the cavity Q with the electron beam present. It was found that the theoretical shifts were substantially larger than those observed experimentally. Better agreement was obtained by comparing the data with predictions based on a self-consistent, nonlinear theory (Fliflet and co-workers, 1982). The mixer system was also used to detect the presence of weak, parasitic modes. (Kreischer and co-workers, 1984c). A number of multimoding regions were identified. These instances of multimoding could be due to a relatively thick beam coupling to two or more modes, or to nonlinear excitation of passive modes (Nusinovich, 1981). We are continuing our study of mode behavior in the oversized cavities that will be required for high power operation.

Recently, we have completed an investigation of surface modes, and in particular whispering gallery modes (Danly and co-workers, 1985a). This class of modes can be defined as $TE_{m,p,q}$ modes where $(1\text{-}m^2/\nu_{mp}^2) \ll 1$, where ν_{mp} is the p^{th} nonzero root of $J'_m(x)$. They are of interest in high power devices because of the potential for reduced mode competition and improved mode stability. However, because the electron beam is located close to the resonator walls, it is important to identify the problems associated with beam alignment and stability at high magnetic fields. Operation was achieved in the $TE_{6,1,1}$ mode at 143 GHz, and single mode emission was observed over a wide range of operating conditions. No competition was evident from the nearest potential mode, the $TE_{0,2,1}$ at 134 GHz. An output power of 112 kW was measured at 65 kV and 8.8 A, corresponding to a total efficiency of 20%. Higher efficiencies were obtained at lower currents, with a peak value of 26% occuring at 3.7 A. In addition, a quasioptical coupler (Vlasov, Zagryadskaya, and Petelin, 1975) was designed and constructed to convert the $TE_{6,1,1}$ radiation into a linearly polarized, Gaussian-like beam. A diagram of this antenna is shown in Fig. 4. The radiation, which propagates in a helical path along the walls of the waveguide, is radiated from the straight edge of the antenna. This radiation is then converted by a cylindrical reflector into a collimated, polarized beam. Far field scans were made in the x′-y plane. These measurements indicated that the conversion efficiency of this coupler was 80-90%, and that the cross-polarization was lower by 25 dB. The use of this converter in conjunction with megawatt gyrotrons appears very attractive.

Strong second harmonic emission (at $2\omega_c$) is known to be produced by gyrotrons operating at the fundamental (Byerly and co-workers, 1984). Harmonic emission has been detected from a Varian 28 GHz gyrotron (Danly, Mulligan, and Temkin, 1985). It is important to develop an understanding of the mechanisms leading to this emission because such radiation could excessively heat and damage components in high power, cw devices. Frequency measurements have been used on the MIT experiment to identify eight second harmonic cavity modes over a range of 200-300 GHz. The measured spectrum is shown in Fig. 5. The highest power measured was 25 kW in the $TE_{11,2,1}$ mode at 241 GHz, with a corresponding efficiency of 7%. The stronger and more stable $TE_{m,p,q}$ modes were largely characterized by a low radial number p. It was found that the strongest harmonic emission occurred at magnetic fields at which minimal fundamental radiation was generated. Some instances of simultaneous $2\omega_c$ radiation were also observed. It is believed that when the fundamental modes are strongly excited, they tend to suppress, but not necessarily prevent, excitation of harmonic modes. Therefore, strong harmonic radiation is most likely in those regions devoid of fundamental modes. A theoretical analysis indicates that second harmonic modes could be excited with high efficiency in megawatt gyrotrons, and therefore may pose a serious problem.

DESIGN OF MEGAWATT GYROTRONS

We have recently begun the design and construction of a 1 MW, 120 GHz gyrotron experiment which should be operational in early 1986. As the first step, the design parameters of a gyromonotron capable of such powers have been determined (Kreischer and co-workers, 1985). This design study was based on a generalized nonlinear model of the interaction between the beam and rf field (Danly and Temkin, 1985). It was found that for a $\mathrm{TE}_{m,p,q}$ mode the transverse efficiency is a function of only the following three normalized variables:

$$\begin{aligned}
\mu &\equiv \pi\left(\frac{\beta_\perp^2}{\beta_\parallel}\right)\left(\frac{L}{\lambda}\right)\\
\Delta &\equiv \frac{2}{\beta_\perp^2}\left(1-\frac{n\omega_\mathrm{c}}{\omega}\right)\\
F &\equiv \frac{E_0\beta_\perp^{n-4}}{Bc}\left(\frac{n^{n-1}}{2^{n-1}n!}\right)J_{\mathrm{m}\pm\mathrm{n}}\left(\frac{\omega R_\mathrm{e}}{c}\right)
\end{aligned} \tag{1}$$

In these equations, $\beta_\perp = v_\perp/c$ and $\beta_\parallel = v_\parallel/c$, where $v_\perp$ and $v_\parallel$ are the perpendicular and parallel electron velocities respectively, B is the static magnetic field, λ is the wavelength, and n is the harmonic number. The length L characterizes the width of the axial field profile. The parameter Δ indicates the detuning between ω_c, the initial cyclotron frequency, and ω, the oscillation frequency. The coupling strength between the beam and rf field is given by the parameter F. The azimuthal component of the rf field is assumed to have the form $E_\theta = E_0 J_\mathrm{m}'(\omega r/c)\exp(-2z/L)^2\cos(\omega t - m\theta)$. The Bessel function $J_{\mathrm{m}\pm\mathrm{n}}$ in (1) is a measure of the harmonic content of the rf field at the beam radius R_e. The choice of signs depends on the direction of azimuthal rotation of the mode. The transverse efficiency has been numerically calculated for all interactions up to the fifth harmonic. It was found that the maximum transverse efficiencies for the second through fifth harmonics were 0.72,0.57,0.45, and 0.37 respectively. An example of these calculations is shown in

Fig. 6 for the fundamental interaction and a Gaussian axial field profile. In this plot, the efficiency has been optimized with respect to Δ at each value of F and μ. The calculation of the efficiency in terms of generalized parameters allows the straightforward design and optimization of gyrotrons operating at any frequency and power.

By expressing the technological constraints of the gyrotron in terms of the parameters defined in (1), the permissable design parameters of megawatt gyrotrons were determined. Constraints that were considered include ohmic heating of the walls, voltage depression of the beam, reduced coupling between the beam and rf field due to beam thickness, and efficiency degradation due to space charge forces within the beam. An example of the accessible operating regions is given in Fig. 7 for a 1 MW, 120 GHz gyromonotron. The upper limit on F is set by the cavity wall losses, which were limited in this study to 2 kW/cm^2. The lower boundary is based on a 10% limit on the beam voltage depression. This graph indicates that the high efficiency regions become more accessible as the cathode voltage is decreased. It was found that lower order modes (i.e., modes with lower ν_{mp}) can be utilized at lower voltages, but the constraints based on current limitations are difficult to satisfy. An 80 kV, 29 A design was selected as the basis our 1 MW experiment. The main parameters are listed in Table 1.

The methodology just described is general and can easily be adapted to other frequencies and output powers. For example, it was used as an aid in the design of both our 100 kW experiments and the 10 kW diagnostic gyrotron to be used on TARA at MIT (Woskoboinikow and co-workers, 1985). Multimegawatt operation was also analyzed. The dependence of the major gyrotron parameters on the output power can be seen in Fig. 8. These plots are based on an output frequency of 120 GHz, an efficiency of 48% and ohmic wall losses in the cavity of 2 kW/cm^2 (at room temperature). The designs at each power level have been optimized and represent operation in the lowest order mode possible. These figures show that the beam current and cavity radius are the parameters that change most quickly as the power is increased. As the power is raised from 100 kW to 10 MW, the current increases from 4 A to 234 A, while the radius changes by an order of magnitude, from 0.15 cm to 1.87 cm. It is interesting to note that as the power increases, the shape of the cavity changes. At low power the length is substantially larger than the radius, while for the 10 MW design the opposite is true. It is anticipated that, as a result of this change, the 10 MW cavity will exhibit unique characteristics that will require further theoretical and experimental investigation.

A 10 MW gyromonotron design was recently completed, and its major parameters are listed in Table 1. This design was obtained by assuming modest improvements in various constraints, as can be seen be comparing the 1 and 10 MW designs. The primary difference is the large cavity radius needed for 10 MW output powers, which implies operation in a high order mode. As a result, it is likely that mode competition will be the most important issue to resolve before 10 MW sources can be developed. Past experimental results suggest that high frequency gyrotrons with single cavities and operating in isolated, asymmetric modes are capable of single mode emission up to the 1 MW level. At higher powers, new approaches will be required to excite the desired mode. One approach would be to reduce the cavity radius by utilizing advanced cavity designs that can tolerate higher wall loadings. Techniques based on mode discrimination may also be feasible. For single cavity devices, a coaxial insert could be used to eliminate volume modes and reduce the number of competing modes. In this case one would operate in a surface mode with the beam near the cavity wall, as has been successfully demonstrated at MIT. Slots in the cavity walls could also be used to discriminate against parasitic modes. Optical techniques that have been successfully used in conjunction with lasers may also be viable.

In addition to single cavity devices, multiple cavity configurations such as gyroklystrons or gyrotwystrons could be used to improve mode selectivity. In general, these devices can operate in a lower order mode than a gyromonotron. In addition, they can operate below the starting current of parasitic modes and still achieve high efficiency. These devices are based on prebunching of the beam by a mode that can be controlled, which results in effective discrimination against modes at other frequencies or with different azimuthal field structures. A theoretical analysis of multiple cavity gyroklystrons has recently been completed at MIT (Tran and co-workers, 1985). As with the generalized nonlinear theory previously described, the interaction efficiency was found to be a function of three parameters representing the interaction length, rf field amplitude, and the magnetic field. Based on this theory, a preliminary design of a two-cavity, 10 MW device driven by a 20 kW source has been completed. Both cavities would operate below the threshold current, and as a result the operating mode would be determined solely by the frequency of the input power. Such a device could operate in a symmetric mode, which could then be easily converted into a Gaussian-like, linearly polarized beam using quasioptical techniques.

ECR HEATING SYSTEM

In addition to the gyrotron sources, an ECRH system will require power supplies, and components to convert the radiation into a linearly polarized beam and transmit it to the plasma. The power supplies should be similar to those required for neutral beams (NB) and other rf heating methods. The gyrotron sources should, in fact, be somewhat simpler than those needed for neutral beams because of the lower voltages involved. The recirculating power within the ECRH system should be relatively small because of the high efficiency of the gyrotrons. This could be further reduced by using a depressed collector to recuperate the lost beam energy. Recent studies (Fix and co-workers, 1984) indicate overall efficiencies as high as 90% can be obtained with a two-stage collector. This is in contrast to neutral beams, which will have low efficiency unless negative ion sources, a relatively untested technology, are developed. Even in this case recapturing lost energy associated with unwanted ion species will complicate the fabrication of these sources (Menon, 1983).

Optical techniques appear most suitable for converting and transmitting the rf power because of the high frequencies involved. Quasioptical antennae appear capable of high conversion efficiencies, as was shown in the $TE_{6,1,1}$ experiments at MIT. This experiment also demonstrated the possibility of using a large diameter pipe to optically propagate the beam to the plasma. Therefore, it is likely that simple components can be used to transmit and couple the power to the plasma. At present, the vacuum window is the most difficult component of the overall system. Potential solutions include expanding the rf beam and reducing the power flux before passing it through a large grid window, or designing a windowless system.

In comparison with alternative heating techniques, ECRH has a number of unique advantages. As a result of low loss, high power density transmission techniques, the gyrotrons can be placed well away from the plasma where they can be protected from high neutron and radiation loads. It is envisioned that the gyrotrons would be built with modular components that could be easily replaced when damaged. The need to place the neutral beams close to the reactor results in activation of the internal components, complicating both maintenance and the integration of the NB system into the reactor. A further problem faced by NB sources is control of the power deposition profile during the startup phase, which would require tuning of the particle energy and beam dumps to minimize damage due to shinethrough. In contrast, ECRH offers the potential for excellent spatial control of energy deposition. Ion cyclotron resonance heating, which has become increasingly popular, also offers the advantage of easy transmission and remote placement of the sources. The major problem for ICRH is the development of 1-5 MW antennae. Such powers are an order of magnitude beyond what is presently available (Mullen and Davis, 1984). These launchers must be placed close to the plasma in order to enhance coupling, which results in high particle and radiation loads on the Faraday shields and necessitates active cooling. ICRH antennae will be much more complex than the quasioptical launchers envisioned for ECRH.

In Table 2, the 10 MW gyrotron is compared with a neutral beam module presently being used on TFTR. It is interesting to note that the voltage and current requirements of both systems are very similar, suggesting that the gyrotron could utilize existing NB power supplies and thus be easily integrated into the TFTR experiment. The gyrotron would have much higher efficiency than the 18% associated with the 120 keV component of the neutral beam, and therefore would have less recirculating power. The cooling and vacuum pumping requirements of the gyrotron should also be easier to satisfy.

CONCLUSIONS

In summary, ECRH is becoming recognized as an effective and desirable method for heating plasmas. Experiments indicate that the efficiency of coupling ECR power to the plasma is comparable to that of other heating techniques. In the past the lack of high power sources was considered the primary limitation preventing the use of ECRH. The rapid progress in gyrotron research is quickly eliminating this barrier. Powers up to 10 MW at frequencies above 100 GHz appear feasible based on a modest extrapolation of present technology. It is hoped that the upcoming 1 MW, 120 GHz experiment at MIT will demonstrate the viability of such devices.

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TABLE 1 Comparison of 1 MW and 10 MW Gyromonotrons

Power(MW)	1.0	10.0
Current(A)	29	240
Voltage(kV)	80	90
Total Efficiency(%)	43	46
Velocity Ratio	2.0	2.5
Wall Loading(kW/cm^2)	1.6	2.0
Beam Radius(cm)	0.62	1.8
Cavity Radius(cm)	0.88	1.87
Maximum Current(A)	62	560
Cathode Current Density(A/cm^2)	5	10
Beam Thickness(mm)	0.21	0.30
Cavity Length(cm)	1.33	0.98
Diffractive Q	370	193
Diffractive Q/Q_{min}	1.0	1.0
Magnetic Compression	30	30

TABLE 2 Comparison of a 10 MW, 120 GHz Gyrotron and a TFTR 5 MW Neutral Beam System.

Source	10 MW Gyrotron	5 MW Neutral Beam
Current(A)	240	230
Voltage(kV)	90	120
Efficiency(%)	46	18
Heating Location	Center	120 keV-center 40/60 keV-edge
Species Heated	Electrons	Predominantly Ions

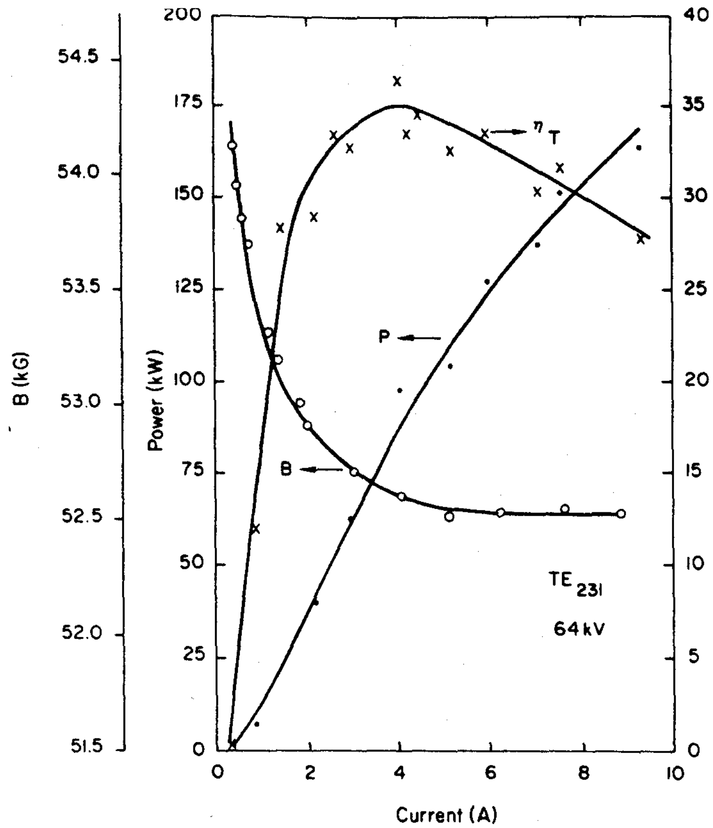

Fig. 1 Measured output power and total efficiency as a function of beam current for the $TE_{2,3,1}$ mode. The magnetic field B has been optimized at each current.

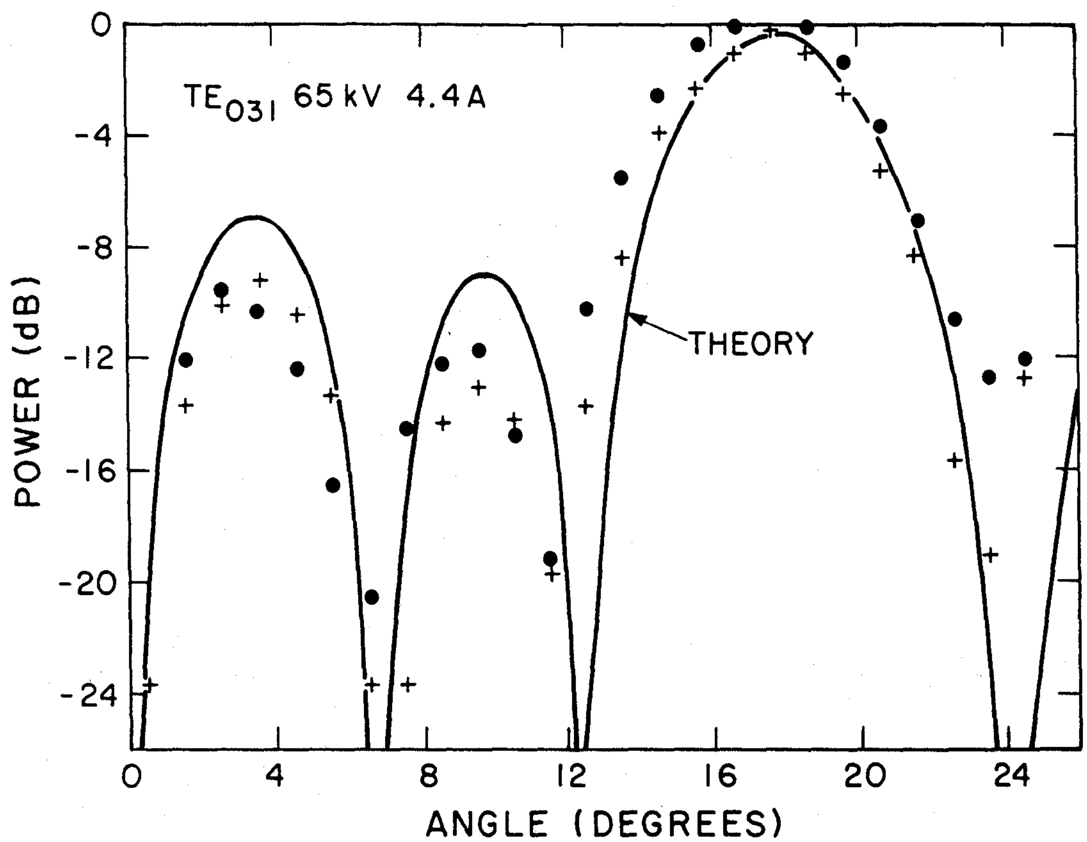

Fig. 2 Comparison of the theoretical and experimental far-field radiation pattern for the $TE_{0,3,1}$ mode.

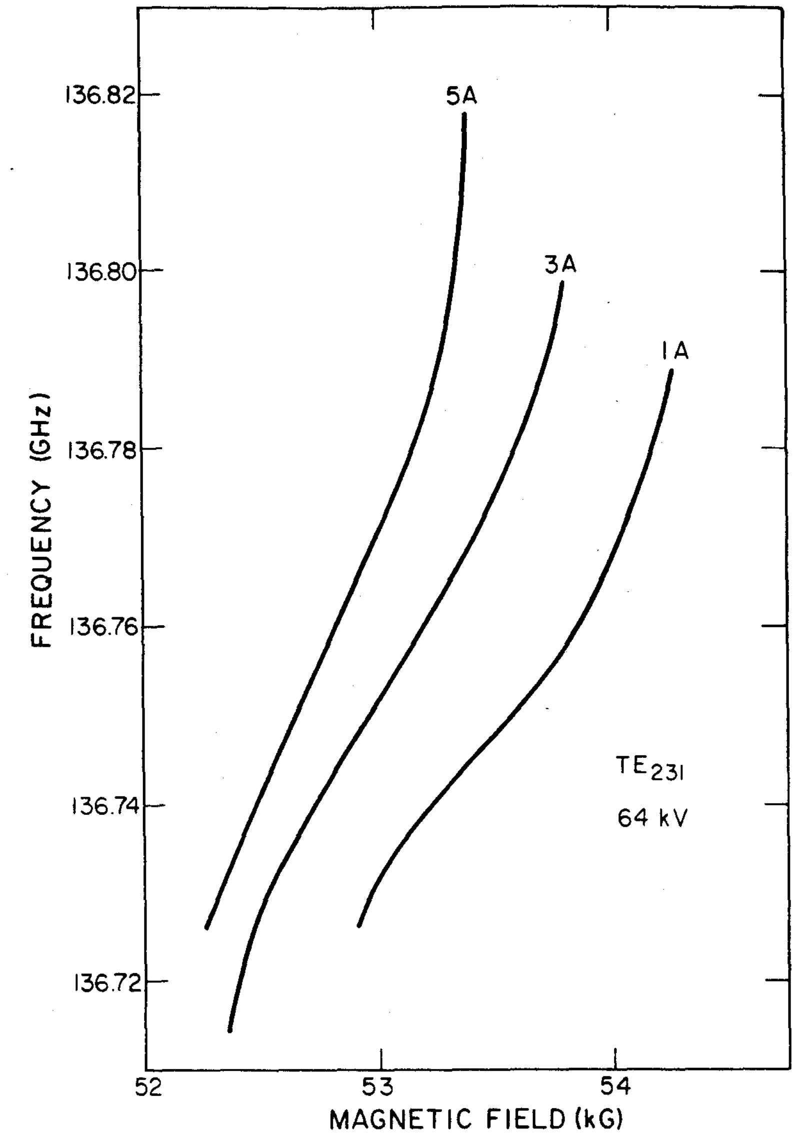

Fig. 3 Dependence of emission frequency on the beam current and magnetic field for the $TE_{2,3,1}$ mode.

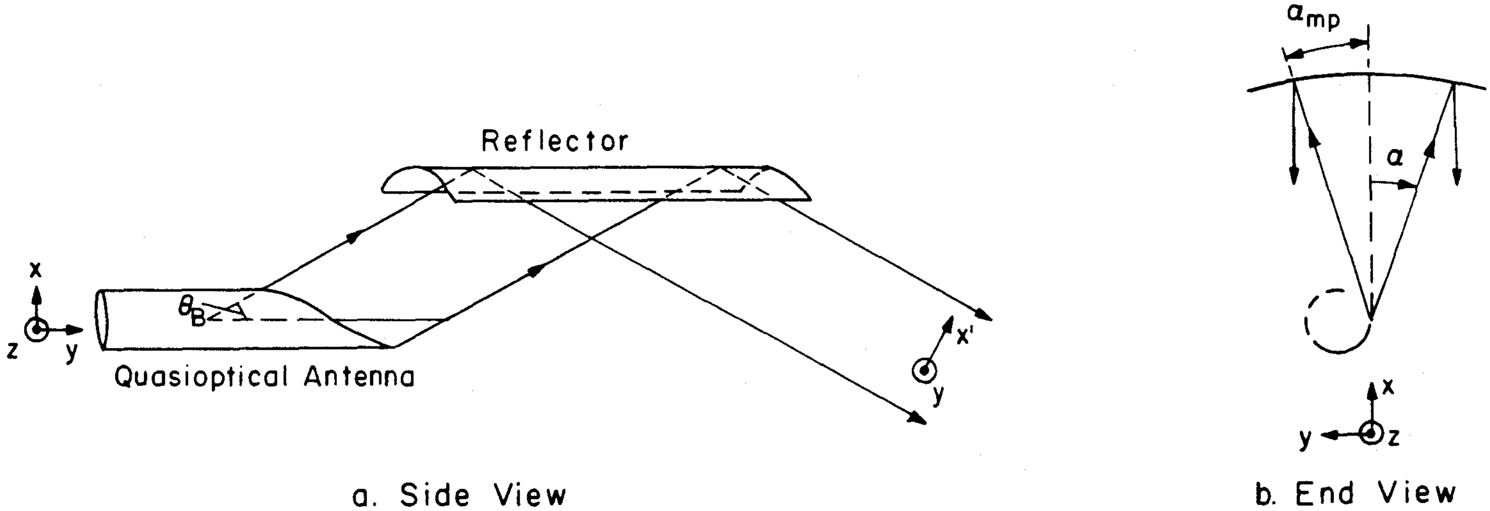

Fig. 4 Side and end view of a quasioptical antenna used in conjunction with the $TE_{6,1,1}$ surface mode.

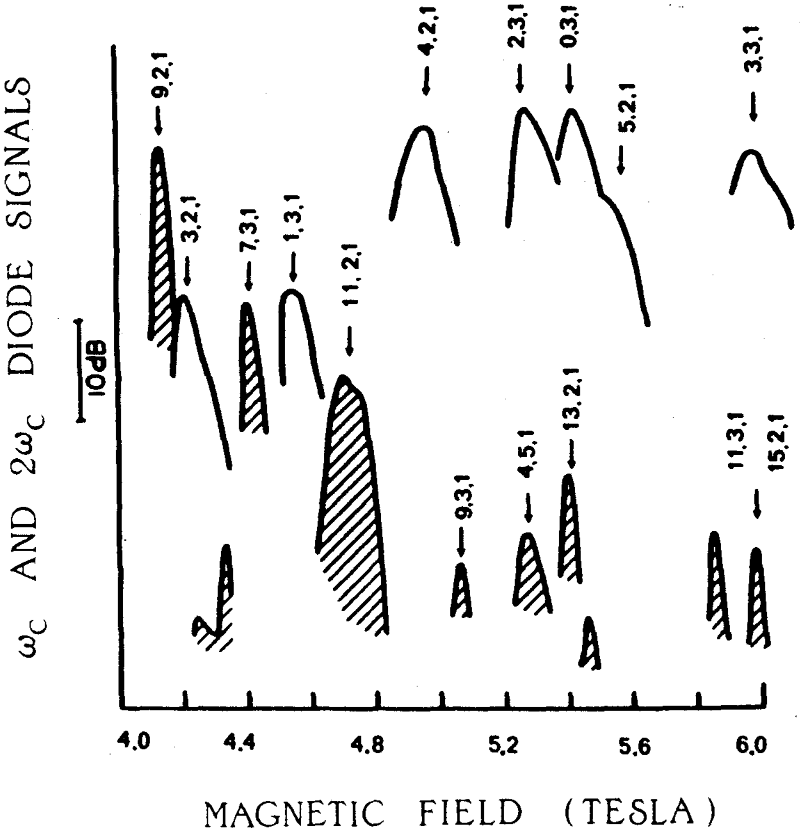

Fig. 5 Diode scan showing both fundamental (unshaded) and second harmonic (shaded) regions of operation.

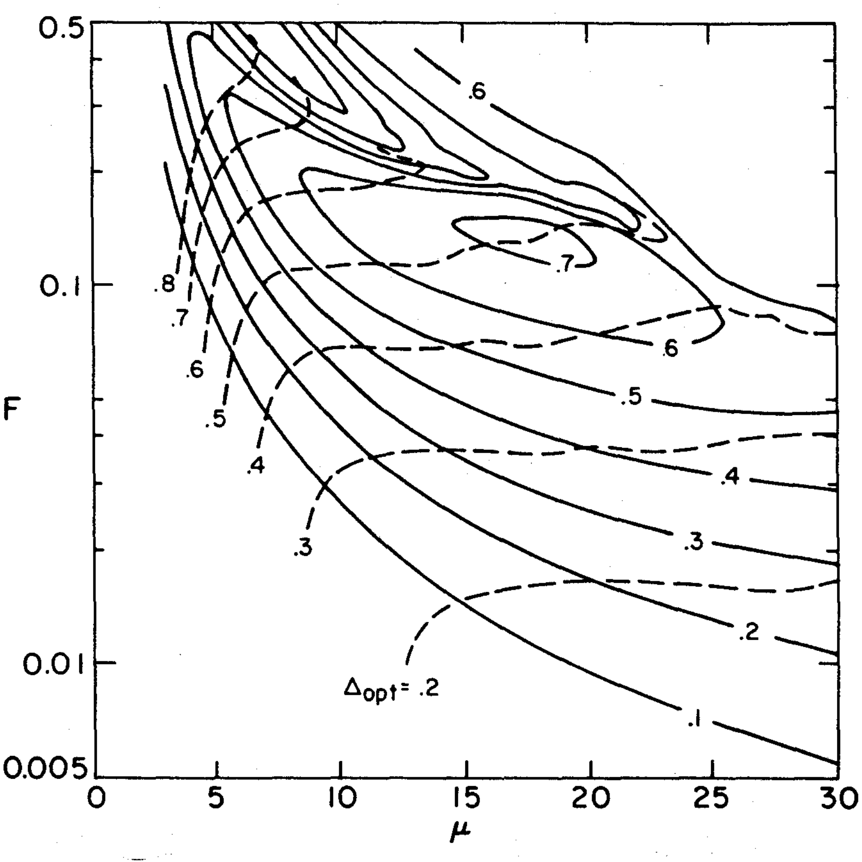

Fig. 6 Contour plot of the transverse efficiency (solid lines) and optimum detuning Δ_{opt} (dashed lines) as a function of normalized field amplitude F and length μ.

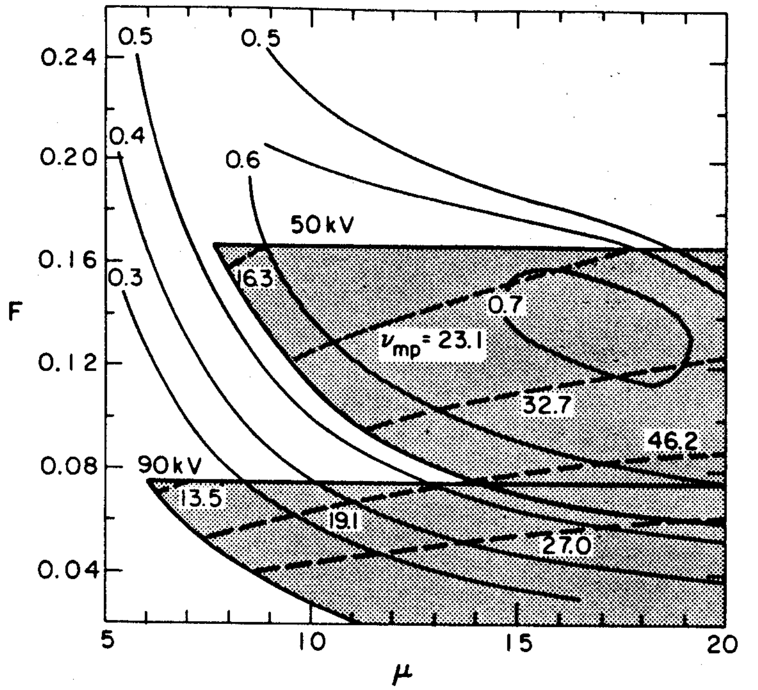

Fig. 7 Allowable operating regions (shaded) for cathode voltages of 50 and 90 kV assuming 1 MW, 120 GHz operation. Dashed lines are mode indices ν_{mp} for symmetric m=0 modes based on an equilibrium in the cavity.

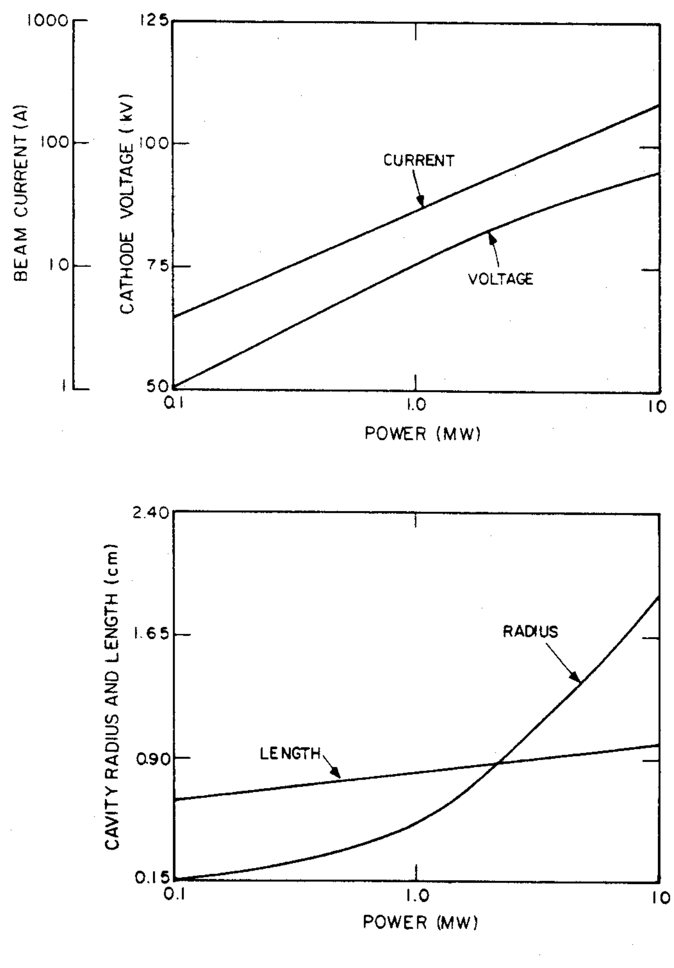

Fig. 8 Characteristics of a 120 GHz gyromonotron as a function of output power.