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ABSTRACT

The operating characteristics of a 140 GHz, pulsed gyrotron are reported. Total efficiencies of 36% and output powers of 175 kW have been obtained in single mode operation. Measurements of power and efficiency have been made for a variety of modes between 120 and 160 GHz, and these results are in good agreement with predictions based on nonlinear theory. The best results have been obtained with isolated, asymmetric modes, such as the TE_{4,2,1}(127.3 GHz), TE_{2,3,1}(136.7 GHz), and the TE_{3,3,1}(155.6 GHz). Although mode competition was found to prevent the TE_{0,3,1} mode (139.5 GHz) from reaching the optimum operating conditions, an output power of 138 kW and total efficiency of 29% were achieved with this mode. A variety of new, highly accurate diagnostic techniques that have been developed to measure the power, frequency, and mode content of the output radiation will be reviewed. In addition, the operating characteristics of both laminar and nonlaminar magnetron injection guns will be compared. The high powers and efficiencies obtained in this experiment are promising for the extension of gyrotron output powers to the megawatt range.
I. INTRODUCTION

One potential method being considered for heating and controlling fusion plasmas is electron cyclotron resonance heating (ECRH). The viability of this approach has been demonstrated in a wide variety of experiments, including recent work in the United States (Hsuan et al. 1984, Prater et al. 1983) and the Soviet Union (Alikaev et al. 1983). As a result of effective coupling to the plasma as well as the ability to locally deposit the rf energy, ECRH can be used not only for bulk heating but also to initiate the plasma and improve its stability. In the past, the primary difficulty in utilizing ECRH has been the lack of high power sources at the appropriate frequencies. However, recent progress in the development of gyrotrons (Andronov et al. 1978, Gaponov et al. 1981, Temkin et al. 1982, Felch 1983, Carmel et al. 1983) has led to the availability of high power, cw sources appropriate for ECRH on present experiments.

This paper will describe our investigation of the operating characteristics of high power (>100 kW), high frequency (>100 GHz) gyrotrons. The importance of developing such devices is supported by studies (Kreischer and Temkin 1983) that indicate that frequencies in excess of 100 GHz will be needed to heat plasmas confined by magnetic fields in excess of 3.5 T. The primary goal of our experiment is to demonstrate that efficient, single mode emission can be achieved in high frequency gyrotrons. In addition, we hope to improve the output coupling of the radiation, and to develop diagnostics suitable for frequencies above 100 GHz. Although the experiment has been operated with a short pulse length (1-2 μsec) and low average power, the resonators have been designed to satisfy the technological constraints that would exist in long pulse or cw devices. Therefore, the ohmic heat dissipation in the resonator walls has been kept below 2 kW/cm² at 100 kW of output power, resulting in relatively oversized cavities. An extensive study of mode suppression and multimoding
(Kreischer et al. 1984) has recently been conducted in order to determine the conditions under which parasitic modes prevent high efficiency operation in the desired mode. In addition, the potential of achieving single mode emission with either isolated, asymmetric modes (TE_{m,p,1}, m \neq 0) or with whispering gallery modes (TE_{m,1,1}, m \gg 1) has been investigated.

Recent improvements of the MIT 140 GHz gyrotron and diagnostics have led to substantial increases in both the output power and efficiency of the device. A variety of modifications have resulted in output powers as high as 175 kW, and peak total efficiencies of 36%. These modifications include an improvement in the absorptivity of our calorimeter, which has eliminated feedback into the gyrotron, a new cavity with a smoother wall finish, and better alignment of the tube. In addition, a clearer understanding of the operation of the electron gun and how it can be optimized has been beneficial. The best results have been obtained with isolated, asymmetric modes which are less susceptible to mode competition, such as the TE_{4,2,1}(127.3 GHz), TE_{2,3,1}(136.7 GHz), and the TE_{3,3,1}(155.6 GHz) modes.

The MIT gyrotron is characterized by a number of unique features. The electron beam has been designed to interact with the second radial maximum of the TE_{0,3,1} at 140 GHz. This is in contrast to experiments at 28-60 GHz which typically have the beam at the first maximum. The placement of the beam at higher radial maxima becomes necessary as these devices are scaled to higher frequencies in order to reduce space charge forces due to higher beam densities. Such forces could enhance the velocity spread of the beam and lower the efficiency. Although a larger beam diameter does increase the potential for rf leakage back to the gun, this has not yet been observed in our experiment. The successful operation of magnetron injection guns with magnetic compressions of 25 has also been
achieved. Two guns were constructed by Varian Associates (Felch et al. 1982), one with a laminar flow of electrons and the other with a nonlaminar flow. Computer simulations indicate that both are capable of producing a high quality beam with $v_\perp/v_\parallel = 1.5$ and $\Delta v_\perp/v_\perp \leq \pm 3.5\%$. The fact that high efficiencies have been obtained with both guns indirectly confirms that the velocity spread of the electron beams is indeed small.

The MIT experiment also has the capability of operating at high magnetic fields. The resonator field is provided by a water-cooled Bitter magnet capable of producing up to 11 T. This magnet has a field homogeneity of $\pm 0.5\%$ over the cavity region, which is adequate for maintaining the beam-rf field resonance. The magnet has a 10.5 cm diameter bore which allows sufficient clearance for the gyrotron tube to be maneuvered within the bore until proper alignment is achieved. Attached to the Bitter magnet are a pair of auxiliary coils that are used to adjust the field in the cathode region. These have proven extremely useful in optimizing the operation of the guns. In addition, they have provided the capability of operating at very high frequencies. By maintaining the optimum field in the cathode region and raising the resonator field, fundamental radiation in excess of 200 GHz has been generated.

Table 1 gives an indication of the versatility of the MIT experiment. This table lists the original design parameters as well as the operating ranges that have been achieved thus far. Although the experiment was initially designed to generate 140 GHz in the TE$_{0,3,1}$ mode, it has been possible to excite a wide variety of fundamental modes with frequencies from 110 to 216 GHz. The large number of modes excited is the result of the relatively dense spectrum of the oversized cavity, as well as the ability to operate the electron guns over a wide range of magnetic compression. Second harmonic emission has also been detected, with measured frequencies as high as 300 GHz and powers as high as
25 kW (Byerly et al. 1984).

This paper will be organized in the following manner. In Section 2, the measured powers and efficiencies of a variety of modes will be presented. The good agreement between data for isolated, asymmetric modes and predictions based on nonlinear theory will be shown. In Section 3, the diagnostic techniques used to analyze the performance of the gyrotron will be described. A comparison of the operating characteristics of the laminar and nonlaminar guns will be made in Section 4. Finally, in Section 5 the conclusions of this paper will be reiterated and the implications of these results for generation of powers approaching 1 MW at frequencies above 100 GHz will be explored.
2. EXPERIMENTAL RESULTS

The MIT gyrotron was first operated in early 1982, and 100 kW was generated at 140 GHz shortly thereafter. A detailed description of the design and initial operation of the experiment can be found in an earlier paper (Temkin et al. 1982). An extensive effort was subsequently made to understand and improve the operating characteristics of the device. In particular, modifications were made to improve the efficiency, which initially was about a factor of two below theoretical predictions. As a result of these efforts, the measured efficiencies are now in good agreement with nonlinear theory.

A variety of factors are responsible for the significant improvement in operation. A new calorimetric system has been built that has greater absorptivity than the original system. The first calorimeter was an unmodified Scientech, Inc., disc calorimeter with a 2.5 cm diameter active surface. This surface was placed close to the output waveguide in order to minimize rf leakage. This increased the potential of feedback into the gyrotron that could adversely affect operation. The new system consists of a disc calorimeter with a 10 cm diameter surface and a thicker layer of absorbing paint. The additional paint has substantially increased absorption, while the larger surface allows the calorimeter to be placed farther from the waveguide, reducing the likelihood that power will be reflected back into the gyrotron. A more detailed description of this system will be given in the next section.

Improvements have also been made in the fabrication of the cavities. As a result of the small dimensions of the resonator, it was concluded that direct machining of the internal surfaces was impractical. Instead, stainless steel mandrils have been machined with the correct profile, and copper cavities have been electroformed. Initially, the quality of the internal walls was poor because of scratches introduced when extracting the mandril and
impurities in the copper solution. However, these problems have been resolved, and we are now confident that power loss in the cavity walls has been reduced considerably.

Finally, we have developed a better understanding of the operating characteristics of the gyrotron and the best ways to optimize its performance. Improvements have occurred as a result of better alignment techniques and operation of the guns under conditions that produce the highest quality beam. Alignment is critical in high frequency devices in order to minimize beam interception and ensure the strongest coupling to the rf field. Misalignment of the beam center by more than $\lambda/8$ can seriously reduce the peak efficiency. In our case, this margin of error is 0.25 mm. As a result, the support mechanism for the tube and the procedure for aligning it were serious considerations. It was found that operating the gyrotron with a low beam current and deliberately intercepting the beam at the cavity entrance was the best method for locating and centering the beam. In addition to improving alignment, a systematic study of the dependence of efficiency on the operating parameters was conducted. It was found that for a given cathode electric field, there is a cathode magnetic field that produces the most stable operation and the highest power. This study also led to the conclusion that higher efficiencies could be achieved at 65 kV, rather than at the higher voltages tried initially.

Figure 1(a) shows a plot of the optimum power and efficiency as a function of beam current for the TE_{2,3,1} mode at 136.7 GHz using the nonlaminar gun. The relatively small scatter in data is a good indication that our power measurement techniques are quite accurate. In order to achieve the optimum conditions at each current, it was necessary to adjust the resonator magnetic field to the value shown on the graph. For this particular cavity each mode could be excited over a region of magnetic field with a width of 3-4%. The field that produced the highest efficiency typically was near the lower edge of this
resonance band. For the TE\textsubscript{2,3,1} mode, there is no competing mode in this region, the nearest competitor being the TE\textsubscript{8,1,1} which weakly couples to the beam. As a result, the high efficiency region was accessible and single mode emission was possible. Note that the measured starting current was 0.2 A, which agrees with a prediction of 0.26 A based on linear theory (Kreischer and Temkin 1980).

Figure 1(b) is another example of the optimum operating characteristics that can be obtained with an isolated, asymmetric mode, in this case the TE\textsubscript{4,2,1} at 127.3 GHz. The dependence of the output power and total efficiency on the beam current is very similar to that obtained with the TE\textsubscript{2,3,1}, although the peak values are somewhat lower. This similarity is the result of good coupling between the beam and rf field, and the lack of competing modes at lower magnetic fields, which again allows the high efficiency region to be reached. The fact that good results were obtained was somewhat unexpected since the gyrotron was designed for operation at 140 GHz, and one might expect frequency mismatches at components such as the window to adversely affect operation.

Figure 2 shows the optimum power and efficiency as predicted by nonlinear theory for the TE\textsubscript{2,3,1} mode. This graph was obtained using a fast time scale particle simulation, and assumes a Gaussian axial rf field profile, a diffractive Q of 1500, \(v_\perp/v_\parallel = 1.5\), and no beam thickness. A code developed by Fliflet (Fliflet and Read 1981) that calculates the rf axial field profile inside a cavity indicates that a Gaussian is a good representation of the field. The similarities of Figs. 1(a) and 2 suggests that the nonlinear theory used to describe the interaction between the beam and rf field is basically correct. Both show the efficiency peaking at about 4 A, and dropping at higher currents as the rf field becomes too strong and causes energy to be transferred back to the beam. In order to shift the optimum efficiency to a higher current, it would be necessary to lower the cavity diffractive
Q from the design value of 1500 to 850. This would result in output powers in excess of 200 kW with currents of 8-9 A.

Unfortunately, a comparison of the peak efficiencies shown in Figs. 1(a) and 2 is not valid because of uncertainty about the $v_\perp$ and $v_\parallel$ of the beam. Although the design value of 1.5 was used for the velocity ratio in Fig. 2, it should be noted that simulations of the nonlaminar gun (Felch et al. 1982) indicate that $v_\perp/v_\parallel$ as high as 2 can be achieved with a low velocity spread. If the gun were operating with $v_\perp/v_\parallel=2$, then the expected peak efficiency would be 48% at 4.2 A. There are a variety of reasons that could account for the lower measured efficiency. These include the beam thickness, losses in the window and transmission waveguide, and a lower ohmic Q than predicted by theory due to fabrication imperfections.

The beam current at which the efficiency peaks can be used to provide information about the total Q, $Q_T$, of the cavity. Using nonlinear theory for the fundamental interaction based on the Gaussian rf profile $\exp(-2z/L)^2$, where $z$ is the axial coordinate (Nusinovich and Erm 1972), one can show that the efficiency of the TE$_{m,p,1}$ mode, after optimizing with respect to the magnetic field, depends only on the parameters

$$I_o = \frac{0.6 \times 10^{-4} Q_T I(A) \left( \frac{v_\perp}{v_\parallel} \right)^4 \left( \frac{L}{\lambda} \right)^3 J_{m\pm 1}^2(k_\perp R_c)}{(\nu_{mp}^2 - m^2) J_m^2(\nu_{mp})}$$

$$\mu = \frac{\pi}{c} \left( \frac{v_\perp}{v_\parallel} \right) \left( \frac{L}{\lambda} \right)$$

In these equations, $I$ is the beam current, $k_\perp = \nu_{mp}/R_o$ where $R_o$ is the cavity radius, and $\nu_{mp}$ is the $p$th zero of $J_m^2(x) = 0$. The choice of signs in $J_{m\pm 1}$ depends on the direction of azimuthal rotation of the mode. Since the mode and cathode voltage are known, and the beam radius $R_c$ can be determined from alignment techniques, the unknown parameters are $L/\lambda, v_\perp/v_\parallel$, and $Q_T$. It was found that for $6 \leq L/\lambda \leq 8$ and $1.3 \leq v_\perp/v_\parallel \leq 2.0$, where the design values are 7.1 and 1.5 respectively, the beam current at which the efficiency peaks
varies by less than ±5% when \( L/\lambda \) and \( v_\perp/v_\parallel \) were varied and \( Q_T \) was held fixed. As a result, the efficiency peak location depends primarily on \( Q_T \). The total \( Q \) was calculated to be 1300±100 based on Figs. 1(a) and (b), which is within 5% of the \( Q \) based on computer simulations.

Figure 1(c) shows the best efficiency and power that could be obtained with the \( \text{TE}_{0,2,1} \) mode at 139.5 GHz. This mode is situated near the \( \text{TE}_{2,3,1} \) mode, which is excited at lower magnetic fields and prevents access to the high efficiency region of the \( \text{TE}_{0,3,1} \). As a result, the peak efficiency for the \( \text{TE}_{0,3,1} \) is below 30%. The effect of not being able to reach the optimum magnetic field can be seen in Fig. 3. Here the optimum field, defined in terms of the detuning parameter \( x = 2(\omega_c - \omega)/Lv_\parallel \), is plotted as a function of beam current. If this optimum point could be reached, then a peak efficiency comparable to that of the \( \text{TE}_{2,3,1} \) would be expected since the \( Q \) and beam-rf field coupling for the two modes are virtually identical. However, Fig. 3 shows the actual \( x \) that could be reached in the experiment before mode jumping (Dialetis and Chu 1983) occurred, and the best efficiency that would be expected based on these values. It can be seen that mode competition has reduced the peak efficiency from 40% to 36%. This problem is one that affects all higher order symmetric \( \text{TE}_{0,p,1} \) modes (\( p \geq 2 \)), since all suffer competition from neighboring \( \text{TE}_{2,p,1} \) modes.

Table 2 lists the best results that have been obtained thus far using the nonlaminar electron gun. The strongest modes have been excited between 125 and 155 GHz, but fundamental radiation as high as 200 GHz has been detected. These maximum values were obtained by varying both the anode and cathode voltages and the cathode magnetic field. The peak efficiencies generally occurred between 4-5 A, while the peak powers were measured at the maximum beam currents. For the \( \text{TE}_{0,3,1} \) and \( \text{TE}_{4,2,1} \) modes, higher
powers were obtained than shown in Figs. 1(b) and (c) by operating at slightly higher voltages (68-70 kV). Table 2 indicates the relatively dense mode spectrum that is found in oversized cavities. One can predict which modes will be strongly excited by noting that the strength of the coupling between the mode and beam scales as $J_{m \pm 1}^2 (k_{\perp} R_e)$ (Kreischer and Temkin 1983), For our experiment, $k_{\perp} R_e = 5.3$ for a magnetic compression of 25 at 140 GHz. Analysis of Table 2 indicates that all the modes shown do couple strongly at their respective frequencies, and that the only modes absent are those with $m \geq 7$, in particular the $\text{TE}_{m,1,1}$ whispering gallery modes.
3. DIAGNOSTICS

In order to analyze the operation of a gyrotron, a variety of diagnostics capable of measuring power, frequency, and mode content are required. As a result of the general lack of diagnostic equipment suitable for short pulse operation at frequencies greater than 100 GHz, it was necessary for us to develop a variety of new techniques capable of high quality measurements. These diagnostics had to be accurate in order to make the comparison with theory reliable, and sensitive enough to identify weak, parasitic modes that could cause unacceptable heating in long pulse and cw devices.

Power measurements were made using a thermoelectric calorimeter modified in the manner suggested by Blaney (Blaney 1980). The calorimeter used was Scientech, Inc., model 36-0401, which consists of a 10 cm diameter aluminum plate covered with a uniform layer of 3M Nextel paint approximately 0.1 mm thick. This plate is attached to a heat sink by an array of thermoelectric elements. These elements sense the temperature rise of the plate and also serve as a thermal conduction path to the heat sink. The calorimeter effectively absorbs radiation in the 0.25 to 35 micron range, but in the millimeter region much of the radiation passes through the paint to be reflected off the metal plate and back towards the source. This problem was alleviated by adding additional Nextel paint to the surface. An increase of the paint thickness to about 0.3 mm substantially improved the absorption without substantially increasing the response time of about 30 sec. Using this system, we measured average powers as low as 10 mW. A 2.5 cm diameter calorimeter was also available to investigate lower output powers.

A variety of tests were performed in order to calibrate the calorimeter and to check its accuracy. A resistive heater embedded on the back of the aluminum plate was used to check losses due to radiation and conduction. By putting a known amount of power into
the plate via this heater, the accuracy of the meter could be determined. A calibrated, 10 micron laser was used as another check on the accuracy of the calorimeter, and was shone on various areas of the plate in order to determined the uniformity of absorption. This test indicated that the location of power deposition on the plate did not alter the measurement by more than 1%. In order to determine the dependence of absorption on frequency, a dispersive Fourier transform spectrometer was used (Afsar 1984). This device measured the perpendicular reflectivity of the calorimeter from 100 to 400 GHz and showed that the reflectivity was less than 15% for the range of interest (130-180 GHz). This measurement was verified using an impatt diode oscillator capable of producing 10 mW of output power from 135 to 143 GHz. The impatt was also used to determine the dependence of absorption on the angle of incidence of the radiation.

Power measurements were made by placing the calorimeter surface approximately 10 cm from the 2.5 cm diameter output waveguide. This distance was chosen to be as large as possible in order to reduce feedback into the gyrotron and still ensure that most of the power was intercepted by the calorimeter. A video diode was used to monitor the reflected signal, allowing us to simultaneously measure the average power and pulse shape. Measurements were found to be highly reproducible and insensitive to the distance and orientation of the calorimeter with respect to the output waveguide.

In order to identify excited modes, both far field radiation patterns and frequency measurements were used. By combining these techniques, it was possible to identify both parasitic modes in the cavity and mode conversion in the transmission system. The former modes are characterized by different patterns and frequencies than the cavity mode, while the latter have different patterns but the same frequency as the cavity mode. Far field radiation patterns were obtained by scanning with a video diode as well as with sheets of
liquid crystal. The liquid crystal allowed us to quickly obtain a qualitative view of the entire pattern in order to check the symmetry of the pattern as well as determine the number of radial lobes. It confirmed that modes with a rotating azimuthal structure were excited in the gyrotron, as one would expect based on the symmetry of the system. Unfortunately, as a result of the low average power of our experiment and the low absorption of the liquid crystal, this technique only worked when the gyrotron was operating at high output powers and producing about 2 mW/cm² on the liquid crystal surface. The video diode scan, which typically was made about 40 cm from the output waveguide, was slower but allowed a direct comparison with theory. This technique provided good resolution of the mode structure and caused minimal feedback back into the gyrotron. We also attempted to make power measurements by calibrating the diode with our impatt and integrating the power measured in the far field. These results agreed with measurements made using the calorimeter. Unfortunately, uncertainties in the gains of various components caused relatively large error bars, making this technique somewhat impractical.

Figure 4 shows a comparison of the experimental and theoretical far field pattern for the TE₀,₃,₁ mode. The data were 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 normalized output power is plotted as a function of the angle θ with respect to the waveguide axis. The dots and crosses differentiate between data taken on either side of the axis. The theoretical power, based on the far field radiation pattern expected from an open circular waveguide (Chu 1940), is

\[ P = P_0 \frac{(k_\parallel + k \cos \theta) J'_m(k a \sin \theta)}{1 - (k \sin \theta/k_\perp)^2} \]

where \( P_0 \) is a normalization constant, \((\omega/c)^2 = k^2 = k_\parallel^2 + k_\perp^2\), \( k_\perp = \nu_{mp}/a \), and \( a \) is the waveguide radius. This equation shows that the main lobe of the radiation pattern
occurs at $\theta = \sin^{-1}(k_{\perp} / k)$, or $\theta \approx \sin^{-1}(R_o/a)$ if no mode conversion has occurred, where

$R_o$ is the cavity radius. For our experiment, the main lobe of all cavity modes occurs at approximately 18°. Figure 4 shows the agreement between theory and experiment to be quite good. The data also indicates that little mode conversion is occurring in the transmission system. Analysis of the linear uptaper from the cavity to the waveguide (Trulsen 1984) indicates that most conversion occurs into the $TE_{0,2,1}$ mode. The main lobe for this mode should occur at 12.6°. Figure 4 shows that the signal is down by 20 dB at this angle, indicating that virtually no conversion is occurring.

Two techniques were used to measure the frequency, a Fabry-Perot interferometer and a harmonic mixer system (Woskoboinikov et al. 1983). The Fabry-Perot was used primarily to identify weak parasitic modes that were difficult to detect as a result of the high power in the main mode. It was also used in conjunction with a calibrated diode to obtain a rough estimate of the relative power in each of the excited modes. The harmonic mixer is a much faster and more sensitive diagnostic capable of measuring frequency to within a few MHz. In this system, the rf signal is heterodyned with the harmonic of a local oscillator, and the resulting i.f. signal is processed in a surface acoustic wave dispersive delay line. An rf switch in the i.f. circuit is used to gate a 250-300 ns portion of the 1-2 $\mu$sec gyrotron pulse, allowing us to look at any portion of the pulse. This diagnostic is very versatile and was operated over a wide frequency range (100-300 GHz). It was used to measure frequency pulling in the gyrotron and to study multimode operation (Kreischer et al. 1984). Bandwidth measurements were also made, and it was found that when the operation of the gyrotron was optimized, bandwidths as low as the instrumental limit (3 MHz) were possible.
4. ELECTRON GUNS

In addition to using the $\text{TE}_{0,3,1}$ cavity with the nonlaminar gun, the results of which are summarized in Section 2, the $\text{TE}_{0,3,1}$ cavity was also used in conjunction with the laminar gun. In this section, the operating characteristics of the laminar gun will be described and compared with those of the nonlaminar gun. Both guns were designed to operate at 65 kV and 5 A in a cathode magnetic field of 0.22 T (Felch et al. 1982). With these operating conditions, and a resonator magnetic field of 5.6 T, both can produce an electron beam with $v_\perp/v_\parallel = 1.5$ and a beam radius $R_e$ of 1.82 mm. The design specification that the velocity spread $\Delta v_\perp/v_\perp$ be less than $\pm 3.5\%$ has also been satisfied by the two guns. Both operate with a magnetic compression of 25, which is the highest compression yet achieved with a magnetron injection gun. The primary differences between these two guns are the cathode angle and the cathode current density. The nonlaminar gun has a cathode angle of 15° and a current density of 2 A/cm². The laminar gun has a larger angle of 25°, which is necessary to prevent electron orbit intersection and produce the laminar flow. This originally caused the beam thickness to be unacceptably large, and as a result the width of the cathode emitter strip was reduced and the current density was increased to 4 A/cm², decreasing the beam thickness from 4.4 to 3.5 Larmor radii, which is comparable to that of the nonlaminar gun.

The type of electron flow in the cathode region has a substantial effect on the operating characteristics of the electron gun. Computer simulations indicate that the laminar gun is less sensitive to both anode and cathode voltage variations than the nonlaminar gun. For example, for a cathode voltage $V_c$ of 65 kV, the ratio $v_\perp/v_\parallel$ for the nonlaminar gun varies from 1.2 to 2.0 as the anode voltage $V_a$ is raised from 19 to 20.2 kV, while $\Delta v_\perp/v_\perp$ decreases from about $\pm 6.8\%$ to $\pm 3.0\%$. In contrast, the laminar gun maintains a relatively
constant $v_\perp/v_\parallel$ of 1.4-1.5, and a velocity spread between $\pm3.2\%$ and $\pm3.9\%$ as $V_a$ is varied from 20 to 23 kV. Simulations also showed little degradation of beam quality due to space charge forces up to beam currents of 5 A for both guns, although it is expected that the beam characteristics of the nonlaminar gun will deteriorate more quickly at higher currents.

The operating performance achieved with the laminar gun was similar to that obtained with the nonlaminar gun. Stable, single mode operation was possible by optimizing both the cathode and resonator magnetic fields for the mode of interest. Table 3 lists the maximum power and efficiency measured in a variety of modes from 127 to 174 GHz. Of the results shown, the most extensive data were taken for the TE$_{2,3,1}$ and TE$_{3,3,1}$ modes. In both cases, power and efficiency were measured for a variety of beam currents. The efficiencies and powers obtained with the laminar gun were generally lower than for the nonlaminar gun. Comparing the TE$_{2,3,1}$ results, the laminar gun achieved a peak efficiency of 25%, down from the 36% obtained with the nonlaminar gun. This may again be an indication that the nonlaminar gun is operating with a higher velocity ratio than 1.5. If the laminar gun were operating at the highest $v_\perp/v_\parallel$ that it can produce, which simulations indicate is 1.5, then a large part of the above difference in efficiency could be accounted for by the fact that the nonlaminar gun can reach a ratio of 2.0 with a low velocity spread.

Table 3 suggests that better results can be obtained with the laminar gun by going to higher frequencies. This is best indicated by comparing the TE$_{2,3,1}$ and TE$_{3,3,1}$ results, with peak efficiencies of 25% and 30% respectively. This difference may be due to the higher magnetic compression that was required in order to excite the TE$_{3,3,1}$ mode. It was found that for a given $V_c$ and $V_a$, there was a fixed cathode magnetic field that produced the highest efficiency. Maintaining these conditions in the gun region, higher frequency modes
were excited by going to higher resonator magnetic fields, thus increasing the compression and raising the velocity ratio. This suggests that high efficiency operation at frequencies approaching 200 GHz should be possible with the laminar gun. Operation at these high frequencies may be the subject of a future investigation.

Beam mirroring was observed in our experiments with both the laminar and nonlaminar guns, and typically occurred when the cathode magnetic field was set too low. The onset of mirroring was accompanied by increased noise on the current and voltage traces, as well as an increase in the internal pressure of the gyrotron tube. In order to check the applicability of adiabatic theory in describing the behavior of the guns, the electron parallel velocity was calculated using this theory, assuming the experimental conditions that existed when mirroring started. It was found that for the laminar gun, $v_{||}$ was close to zero as one would expect. However, mirroring occurred in the nonlaminar gun at a much higher cathode magnetic field than predicted by adiabatic theory, suggesting that this theory may be inadequate for explaining the behavior of nonlaminar electron flows. It should be noted that the power and efficiency results presented in this paper were obtained under conditions in which no beam mirroring was present.

It was possible for us to obtain information about the beam size from our alignment procedure. The gyrotron was aligned by centering one end of the tube in the magnet bore and then moving the other end until beam interception occurred. This allowed us to locate the beam and adjust the tube position until the beam was centered in the cavity. In addition, this technique provided information about the outer diameter of the beam. For example, this method indicated that the laminar beam outer diameter was 3.7 mm for a magnetic compression of 27.7, compared with the expected value of 3.9 mm. In general, the beam size for both guns agreed with the theoretical size based on the diameter of the
emitter strip and the compression.

It was found that the cathode magnetic field $B_k$ was the most important parameter in optimizing the operation of both guns. The best efficiencies were generally achieved by lowering $B_k$ until just before the onset of beam mirroring. This is consistent with adiabatic theory, which predicts that the velocity ratio should increase as $B_k$ decreases. For $V_c=64$ kV and $V_a=19.7$ kV, the nonlaminar gun produced the best results for the modes listed in Table 2 when $B_k$ was between 0.25 and 0.27 T. This is higher than the expected field of 0.22 T based on simulations. Operation at 0.22 T was inaccessible as a result of beam mirroring. For $V_c=64$ kV and $V_a=20.6$ kV, the laminar gun was optimized for the modes in Table 3 for $B_k$ between 0.19 and 0.21 T, somewhat below the design value of 0.22 T.
5. CONCLUSIONS

In this paper, the operating characteristics of the MIT 140 GHz pulsed gyrotron have been described in detail. The primary goal of the experiment was to determine if efficient, single mode emission could be achieved at frequencies above 100 GHz in a pulsed gyrotron designed to satisfy the constraints that would exist in a cw device. Although the primary mode of interest was originally the $\text{TE}_{0,3,1}$, in fact a large number of modes were studied between 100 and 200 GHz, a result of the relatively dense spectrum that exists in the oversized cavity. A survey of these results indicates that the highest efficiencies and powers were achieved with isolated, asymmetric modes. For example, peak total efficiencies of 34% and 36% were measured in the $\text{TE}_{4,2,1}$ and $\text{TE}_{2,3,1}$ modes respectively. In addition, it was possible to generate output powers between 160 and 175 kW with these two modes. An analysis of the rf signal using a harmonic mixer system indicated that both were emitting at a single frequency and that no parasitic modes were being excited in the cavity. These positive results are due to the fact that neither mode has a competing, neighboring mode at lower magnetic fields. In contrast, the highest efficiency that could be achieved with the $\text{TE}_{0,3,1}$ mode was 29%. In this case, competition from the $\text{TE}_{2,3,1}$ prevents access to the high efficiency region, and the 34% to 36% values that should be possible were not achieved. Instead, it was necessary to operate at a higher than optimum magnetic field in order to get single mode emission in the $\text{TE}_{0,3,1}$.

A variety of diagnostic techniques were developed in conjunction with the experiment in order to facilitate the comparison between experimental data and theory. The calorimetric system, based on a modified Scientech, Inc., disc radiometer, is capable of absorbing over 85% of the radiation between 130 and 180 GHz, and causes minimal feedback into the gyrotron. This system proved to be very reliable, and was capable of measuring av-
verage powers as low as 10 mW. Liquid crystal was used to obtain a qualitative view of the far field radiation pattern in order to check its azimuthal symmetry and determine the number of radial lobes. More quantitative data on the far field pattern was acquired using a video diode, and comparisons with theory indicated that in the case of the TE₀,₃,₁ mode little conversion was occurring in the output taper of the cavity. Both a Fabry-Perot and a harmonic mixer system were used to measure the gyrotron emission frequency. The Fabry-Perot proved most useful in detecting weak, parasitic modes in the presence of a strong mode, while the ability of the mixer to measure the frequency to within a few MHz allowed us to make both bandwidth and frequency pulling measurements. As a result of the accuracy of our diagnostics, detailed comparisons between theory and experiment, such as Figs. 1(a) and 2, were feasible. Such comparisons provide the potential of indirectly determining the device parameters from the operating characteristics. For example, the calculation of the total cavity Q based on peak efficiency measurements yielded the same result as computer simulations.

Our investigation of both a laminar and nonlaminar electron gun in conjunction with the TE₀,₃,₁ cavity showed that both are capable of generating high efficiencies and powers at 140 GHz. The operation of both guns was optimized by lowering the cathode magnetic field at fixed anode and cathode voltages until just before the onset of mirroring. The nonlaminar gun typically produced somewhat better results, which may be attributable to the fact that it can generate a beam with \( v_\perp/v_\parallel = 2 \) and low velocity spread, according to simulations, while the maximum laminar gun velocity ratio is 1.5. Better results were achieved with the laminar gun by increasing the magnetic compression, thus raising the velocity ratio, and operating in higher frequency modes. Compressions as high as 35 were achieved with the laminar gun, indicating that the beam has a low velocity spread. We
anticipate that high efficiency operation at frequencies approaching 200 GHz should be possible with this gun.

Our study of high power gyrotrons indicates that the single cavity configuration with linear input and output tapers is capable of generating high efficiencies and powers in a single mode, even when the mode spectrum is relatively dense. We believe that such a design can produce powers in the megawatt range at frequencies above 100 GHz if care is taken when choosing the mode and the beam radius. Our experiment indicates that isolated, asymmetric modes with few competing modes at lower magnetic fields are the best candidates. The probability of obtaining single mode emission can be further improved by placing the beam at a radius at which it weakly couples to parasitic modes. Operating with the beam at a higher radial maximum of the rf field, as was done in our experiment, should be beneficial since the current density in the beam will be lower, reducing the potential for efficiency degradation due to space charge.

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Operating Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (kV)</td>
<td>65</td>
<td>23-80</td>
</tr>
<tr>
<td>Current (A)</td>
<td>5</td>
<td>≤10</td>
</tr>
<tr>
<td>Frequency (GHz): $\omega_c$</td>
<td>140</td>
<td>110-216</td>
</tr>
<tr>
<td>Frequency (GHz): $2\omega_c$</td>
<td>-</td>
<td>209-302</td>
</tr>
<tr>
<td>Magnetic Field (T)</td>
<td>5.4</td>
<td>4.8-8.8</td>
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<tr>
<td>Magnetic Compression</td>
<td>25</td>
<td>18-35</td>
</tr>
<tr>
<td>Peak Power (kW)</td>
<td>100</td>
<td>≤175</td>
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<tr>
<td>Total Efficiency (%)</td>
<td>40</td>
<td>≤36</td>
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<tr>
<td>Current Density (A/cm$^2$):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laminar Gun</td>
<td>4</td>
<td>0.7</td>
</tr>
<tr>
<td>Nonlaminar Gun</td>
<td>2</td>
<td>0-3.6</td>
</tr>
<tr>
<td>Beam Radius (mm)</td>
<td>1.82</td>
<td>1.5-2.1</td>
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Table 1. Comparison of the design parameters and the operating ranges that were actually achieved.
<table>
<thead>
<tr>
<th>Mode</th>
<th>$\nu$(GHz)</th>
<th>Maximum P(kW)</th>
<th>Maximum $\eta$(%)</th>
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<tbody>
<tr>
<td>TE$_{4,2,1}$</td>
<td>127.3</td>
<td>162</td>
<td>34</td>
</tr>
<tr>
<td>TE$_{2,3,1}$</td>
<td>136.7</td>
<td>175</td>
<td>36</td>
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<tr>
<td>TE$_{0,3,1}$</td>
<td>139.5</td>
<td>138</td>
<td>29</td>
</tr>
<tr>
<td>TE$_{5,2,1}$</td>
<td>144.3</td>
<td>&gt; 100</td>
<td>28</td>
</tr>
<tr>
<td>TE$_{3,3,1}$</td>
<td>155.6</td>
<td>116</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 2. Maximum powers and efficiencies obtained with the nonlaminar gun.

Results shown for the TE$_{5,2,1}$ and TE$_{3,3,1}$ modes are based on limited data that may not be optimized.
<table>
<thead>
<tr>
<th>Mode</th>
<th>(\nu) (GHz)</th>
<th>Maximum P (kW)</th>
<th>Maximum (\eta) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE(_{4,2,1})</td>
<td>127.3</td>
<td>67</td>
<td>23</td>
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<tr>
<td>TE(_{2,3,1})</td>
<td>136.7</td>
<td>82</td>
<td>25</td>
</tr>
<tr>
<td>TE(_{0,3,1})</td>
<td>139.5</td>
<td>63</td>
<td>20</td>
</tr>
<tr>
<td>TE(_{3,3,1})</td>
<td>155.6</td>
<td>110</td>
<td>30</td>
</tr>
<tr>
<td>TE(_{4,3,1})</td>
<td>173.9</td>
<td>54</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 3. Maximum powers and efficiencies obtained with the laminar gun.
FIGURES

Figure 1 Measured output power and total efficiency as a function of beam current. The parameter B is the resonator magnetic field that produces the highest efficiency at each current. (a)TE$_{2,3,1}$ (b)TE$_{4,2,1}$ (c)TE$_{0,3,1}$.

Figure 2 Theoretical output power, total efficiency, and optimum magnetic field as a function of beam current. Calculation is based on a Gaussian axial rf field profile and a diffractive Q of 1500.

Figure 3 Comparison of the theoretical total efficiency $\eta_T$ (OPT) obtained when operating at the optimum detuning $X$(OPT), with the theoretical efficiency $\eta_T$(EXP) based on the actual detuning $X$(EXP) achieved experimentally with the TE$_{0,3,1}$ mode.

Figure 4 Comparison of the theoretical and experimental far field radiation pattern for the TE$_{0,3,1}$ mode. The dots and crosses represent data taken on different sides of the axis of symmetry.
Figure 1 (b)
Figure 1 (c)
Figure 2

TE231
64 kV
V_{\perp}/V_{\parallel} = 1.5
Figure 3