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# RECENT OPERATING EXPERIENCE WITH VARIAN 70 GHz AND 140 GHz GYROTRONS*

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## ABSTRACT

The design features and initial test results of Varian 70 GHz and 140 GHz CW gyrotrons are presented. The first experimental 140 GHz tube has achieved an output power of 102 kW at 24% efficiency under pulsed conditions in the desired $TE^{o}_{031}$ cavity mode. Further tests aimed at achieving the design goal of 100 kW CW are currently underway. The 70 GHz tube has achieved an output power of 200 kW under pulsed conditions and possesses a wide dynamic range for output power variations.

## INTRODUCTION

Two new high-power, CW gyrotron oscillators are currently being designed and tested at Varian for use in electron cyclotron resonance heating (ECRH) in magnetic confinement fusion devices. The first of these new tubes has a frequency of 140 GHz, and is designed to generate an output power of 100 kW CW. The second tube has a frequency of 70 GHz and is designed for 200 kW CW operation. These two new tubes at 70 GHz and 140 GHz are similar in many respects to previous gyrotron oscillators developed at Varian. Output power levels in excess of 200 kW CW have been achieved in tubes at 28 GHz, 35 GHz, 56 GHz, and 60 GHz.[1] In addition, 200 kW, 100 ms pulse tubes at 28 GHz, 53 GHz, 60 GHz and 70 GHz have been delivered to various fusion laboratories. In the following, we summarize the basic design of the two new gyrotrons and present initial test results for each of the tubes.

## 140 GHz GYROTRON DESIGN

The design of the 140 GHz tube is centered around an interaction cavity which is resonant in the $TE^{o}_{031}$ mode at 140 GHz. The electron beam is located on the second radial electric field maximum in the cavity rather than the first to facilitate the design of the electron gun. (Placement on the first radial maximum would require a small beam and prohibitively small dimensions in the electron gun.)

The microwave power generated in the cavity diffracts into the output waveguide and exits the tube through a vacuum window. The

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electron beam is collected on the walls of the output waveguide as it follows the diverging magnetic field lines of the superconducting gyrotron magnet. Once the microwaves exit the $TE^{o}_{031}$ cavity, they propagate in the $TE^{o}_{03}$ waveguide mode. Below, we summarize the important aspects of the 140 GHz gyrotron design. Further details of the design have been published elsewhere.[2]

Electron Gun. Varian has recently designed and constructed two magnetron injection guns for 140 GHz gyrotron experiments.[3] The principal difference between the two gun designs was the angle of the cathode emitter. For the present 140 GHz program, we have retained the cathode emitter angles of the earlier guns and modified the other electrode shapes to optimize the performance of the guns for the slightly different voltage, current, and magnetic field requirements of the present tube design. Both guns are designed to operate at a beam voltage of 50 - 60 kV and a beam current of up to 8 A, and to provide a high-quality beam with a perpendicular to parallel velocity ratio, $\alpha$, of 1.5 to 2.0.

The first of the gun designs to be tested has a cathode angle of $15^{o}$ and produces a beam which is somewhat nonlaminar in the acceleration region. The second gun design has a $25^{o}$ cathode angle and generates a beam with laminar electron trajectories. This gun has a thicker beam than the nonlaminar gun and is, therefore, less desirable from the standpoint of beam transmission. However, the beam produced by the laminar gun has a lower velocity spread than that of the nonlaminar gun and is, therefore, less susceptible to electron mirroring at high values of $\alpha$.

Interaction Circuit. During the 140 GHz Gyrotron Development Program two different types of cavities will be tested. The first experimental tube employs a simple, tapered $TE^{o}_{031}$ cavity. Fig. 1 shows the calculated large-signal efficiency plotted as a function of output power for two different beam voltages for the chosen simple, tapered cavity design. The small-signal, start-oscillation conditions for the 140 GHz simple, tapered cavity design are shown in Fig. 2 for the desired $TE^{o}_{031}$ mode and competing $TE^{o}_{231}$ and $TE^{o}_{521}$ modes. Also shown in this figure is the region of parameter space where maximum large-signal efficiency is predicted for the $TE^{o}_{031}$ mode. These calculations indicate that mode competition may limit the efficiency to less than the optimum values predicted in Fig. 1. The average power loading on the cavity walls for this design is about 1.2 $kW/cm^2$ at 100 kW output power, assuming ideal temperature and surface conditions on the copper walls.

The second type of output cavity to be tested is a $TE^{o}_{021}/TE^{o}_{031}$ complex cavity. In this type of cavity, the mode formed by the superposition of the $TE_{021}$ and $TE_{031}$ modes can have significantly less mode competition than a simple, tapered $TE^{o}_{031}$ cavity. Large-signal efficiency calculations for the $TE^{o}_{021}/TE^{o}_{031}$ cavity design to be tested are shown in Fig. 3. We note that a slight tapering of the magnetic field along the length of the cavity serves to increase the efficiency. The average wall loading of the 140 GHz $TE^{o}_{021}/TE^{o}_{031}$ cavity design is somewhat higher than that of the simple, tapered $TE^{o}_{031}$ design.

Output Taper, Collector and Window. Since the output waveguide from the cavity also serves as the electron beam collector, an uptaper from the cavity to the 2.5-inch diameter collector is required. The uptaper employed on the first experimental tube has a linear profile, while succeeding tubes will employ a nonlinear taper which has a calculated mode purity of 98% in the desired $TE_{03}$ mode. The output window is a double-disc design with face cooling between the two ceramic discs provided by a low-loss dielectric fluid.

Superconducting Magnet. The gyrotron magnet is capable of providing the 50-56 kG magnetic field strengths necessary for gyrotron operation at 140 GHz. The main magnetic field is provided by two large coils, while two smaller coils regulate the field in the gun region. Additional transverse coils are used in optimizing beam transmission through the tube.

## INITIAL 140 GHz GYROTRON TEST RESULTS

The first experimental 140 GHz tube incorporates the nonlaminar electron gun design and simple, tapered $TE^o_{031}$ cavity design discussed above. Thus far, tests on the first tube have been carried out only in pulse operation. Initial tests employed a beam voltage of 50 kV and beam currents of up to 8A. The $TE^o_{031}$ mode was readily identified by frequency, and oscillated at 139.70 GHz. In addition, the competing $TE^o_{231}$ and $TE^o_{521}$ modes were also easily detected at frequencies of 137.0 GHz and 144.4 GHz, respectively. Fig. 4 shows a plot of output power and efficiency vs beam current for the $TE_{031}$ mode. A maximum power of 47 kW at 23.7% efficiency is indicated in this plot for a beam current of 4 A. At higher beam currents the efficiency falls quite rapidly. This appears to be due to increased mirroring of the electron beam at higher currents. As attempts to achieve higher $\alpha$ were made by increasing the gun-anode voltage, the efficiency fell.

Following these initial tests at 50 kV, a beam voltage of 60 kV was employed. In general, two effects were observed at the higher beam voltage: 1) higher powers and efficiencies could be obtained at higher beam currents and 2) mode competition with the $TE^o_{231}$ and $TE^o_{521}$ modes was somewhat worse than observed at 50 kV. The first effect was probably due to improved beam quality at the higher voltage. The mode competition problem stemmed from the greater gain bandwidth of the modes at higher beam voltage which, in turn, increased the overlapping of the modes in parameter space. By optimizing the magnetic field and gun-anode voltage for operation at 60 kV, an output power of 102 kW was obtained in the $TE_{031}$ mode at an efficiency of 24.3%. A plot of output power vs beam current is shown in Fig. 5. In Fig. 6, we show a plot of output power vs cavity magnetic field for a constant beam current of 7 A. Here we see the intrusion of the $TE^o_{231}$ and $TE^o_{521}$ competing modes.

In addition to the measurements made on the $TE^o_{031}$ mode, some efforts were made to vary the magnetic field to optimize the output power of the $TE^o_{231}$ mode at 137.0 GHz and the $TE^o_{621}$ mode at 160.6 GHz. In the $TE^o_{231}$ mode, a power of 73 kW was obtained at 24.2% efficiency, and in the $TE^o_{621}$ mode, 106 kW was observed at 27.3% efficiency. Both of these modes were relatively free of mode competition and occupied large regions of parameter space.

During all of the testing performed thus far, there has been no problem in obtaining 100% beam transmission using the transverse steering coils in the gyrotron magnet. Efforts are currently underway to age this tube into CW operation and observe the thermal effects in the cavity, collector and window of high average power operation. Soon after these tests, the same tube will be tested with an electron gun of the alternate design which has laminar beam formation and improved velocity spread characteristics. Following those tests, a tube which has a $TE^{O}_{021}/TE^{O}_{031}$ complex cavity will be tested.

## 70 GHz, 200 kW CW GYROTRON

### 70 GHz GYROTRON DESIGN

Since the 70 GHz, 200 kW CW gyrotron design is in most respects a scaled version of the Varian 60 GHz, 200 kW CW design which has been described in detail in previous work,[1,4,5,6] we will simply enumerate the important features of the design.

The electron gun for the 70 GHz tube includes a few modifications of the electrode shapes used on the 60 GHz tubes in order to optimize the performance of the gun at 70 GHz. Particular attention was given to increasing the range in gun-anode voltage to improve control over the output power level.

The interaction cavity is a scaled version of the $TE^{O}_{011}/TE^{O}_{021}$ complex cavity employed in the 60 GHz tubes.[4,5,6] The 70 GHz tube has a four-inch diameter collector and a 2.5-inch diameter double-disc output window. This combination necessitates the use of an uptaper between the cavity and collector and a downtaper between the collector and output window. Non-linear taper designs are employed and have a calculated mode purity of about 98% for the whole uptaper-collector-downtaper combination. The output window is a scaled version of the 60 GHz design.

### INITIAL 70 GHz GYROTRON TEST RESULTS

Pulsed data were taken at 0.25 to 1.0% duty rates and typically at pulse durations of 0.5 msec with positive magnetic field tapers of 3 to 8% along the axial extent of the cavity. Nominal beam voltage and current were 80 kV and 8.0 amperes, respectively.

Figure 7 shows clearly that by changing the gun anode voltage, the output power varied smoothly from 15-30 kW to 200 kW without mode competition or other instabilities. The dynamic range of 2 kV obtained with the 3.3% taper gave much greater control than the 1 kV commonly seen in gyrotrons without complex cavities. Experimental data showed almost no competition from the $TE_{22}$ mode. The maximum power obtained to date is 208 kW with a 7.7% positive taper. The efficiency was slightly more than 32%; however, for this magnetic field taper the dynamic range is reduced to about 1.4 kV. Peak efficiency for the 3.3% taper was slightly less than 32%. Magnetic field tapers can enhance efficiency, but they can also detrimentally affect beam formation and transmission in the gun and compression regions causing beam interception or mode competition, thus reducing dynamic range, or even efficiency.

Figure 8 shows the variation in rf output power observed for changes in the current of main magnet coil number 1. As the magnet current was increased past the region of maximum power, the output decreased linearly until a point was reached where the oscillator changed modes. It was also noted that peak body current did not exceed 20 mA during normal operation, indicating good beam transmission.

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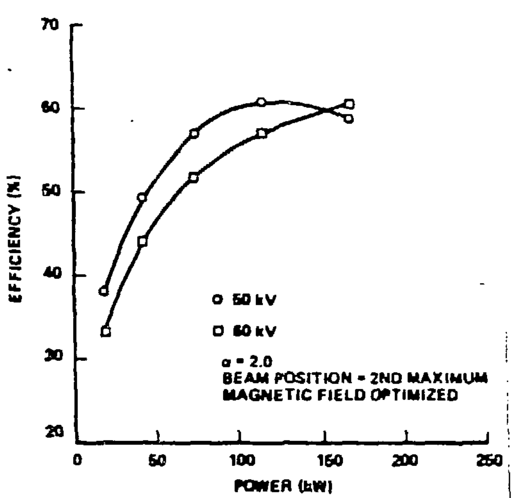


Figure 1. Efficiency vs Output Power for Simple $TE_{031}$ 140 GHz Cavity Designs.

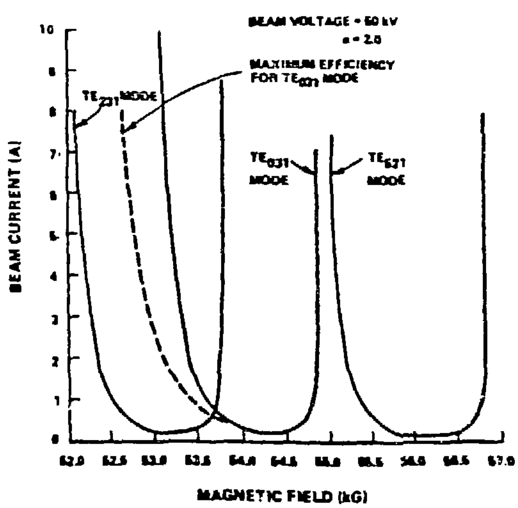


Figure 2. Small-signal Starting Current Calculations for 140 GHz Simple, Tapered Cavity Design. Also Shown is the Region of Parameter Space Where Maximum Large-signal Efficiency is Obtained for the Desired $TE_{031}$ Mode.

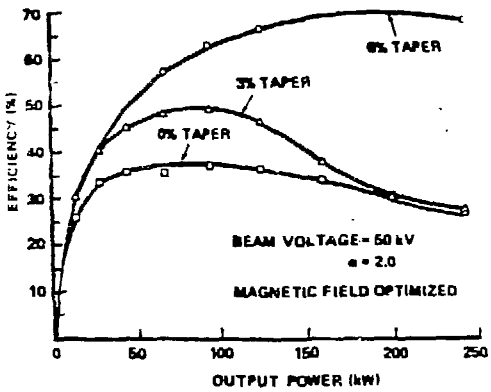


Figure 3. Calculated Efficiency vs Output Power for Different Magnetic Field Tapers for the 140 GHz $TE_{021}/TE_{031}$ Cavity Design.

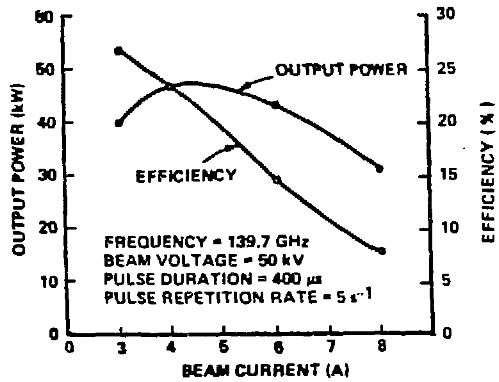


Figure 4. Output Power and Efficiency vs Beam Current for 140 GHz Gyrotron Operation in the $TE_{031}$ Mode with a Beam Voltage of 50 kV.

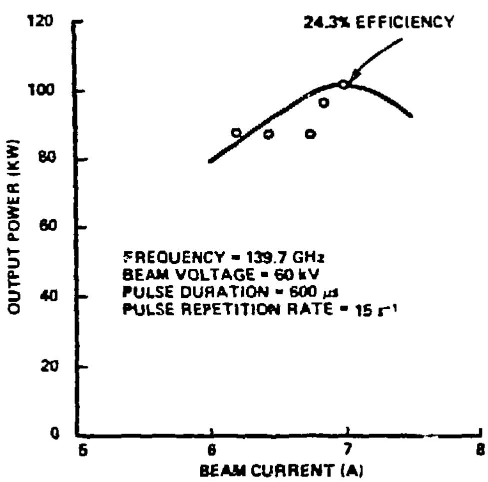


Figure 5. Output Power vs Beam Current for 140 GHz Gyrotron Operation in the $TE_{031}$ Mode with a Beam Voltage of 60 kV and Optimized Magnetic Field.

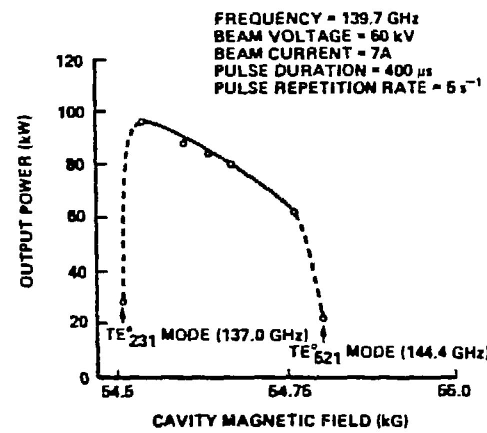


Figure 6. Output Power vs Cavity Magnetic Field for 140 GHz Gyrotron Operation in the $TE_{031}$ Mode with a Beam Voltage of 60 kV and a Beam Current of 7 A.

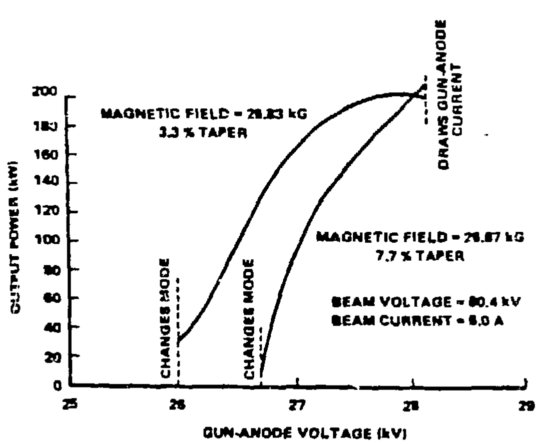


Figure 7. Output Power vs Gun-Anode Voltage for Two Magnetic Field Configurations.

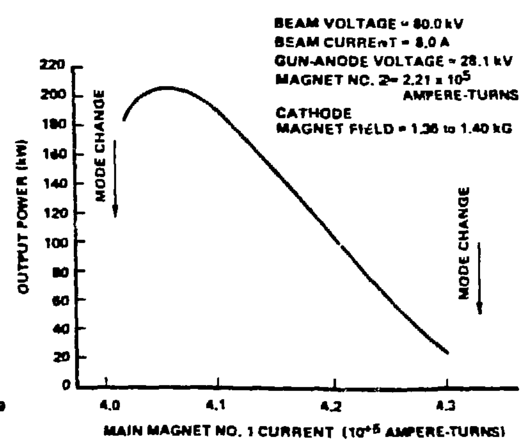


Figure 8. Peak Power Out vs Magnet No. 1.