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FOR POWER LEVELS UP TO 1 MW CW

VARIAN ASSOCIATES, INC.

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DESIGN AND OPERATION OF 140 GHz GYROTRON OSCILLATORS FOR POWER LEVELS UP TO 1 MW CW* (U)

(This entire article is unclassified)

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ABSTRACT

Varian has designed and tested 140 GHz gyrotron oscillators that have generated output powers of 100 kW CW and 200 kW for 1 ms pulses. Upcoming tubes will be designed to operate at power levels of 200 kW CW and ultimately up to 1 MW CW. The important design considerations which are addressed in the higher power tubes include the design of the electron gun, interaction circuit, and output window. These issues will be discussed and the results of the earlier 140 GHz gyrotron work at Varian will be summarized.

INTRODUCTION

Varian is currently developing 140 GHz gyrotrons for use in electron cyclotron resonance heating (ECRH) of magnetically-confined plasmas. Varian 200 kW CW gyrotrons at frequencies of 28, 35, 53, 56, 60 and 70 GHz have been delivered and are successfully operating in ECRH experiments at laboratories around the world^{1,2}. The original goal of the 140 GHz Gyrotron Development Program was to produce tubes with an output power capability of 100 kW CW. We accomplished this goal with our second experimental tube.

Our present goal is to develop gyrotrons to operate at 1 MW CW at 140 GHz. The approach which has been chosen involves using cavities employing the whispering gallery modes, such as the $TE_{15,1,1}$ or $TE_{15,2,1}$ modes. These cavities are larger in size than the TE_{03} class of cavities³ which have been used effectively in the existing 140 GHz gyrotrons operating at the 100 to 200 kW level. The larger cavities reduce the power densities associated with the cavity wall currents and allow the use of larger, lower current density electron beams.

The choice of the whispering gallery mode type is based on extensive analysis done at Varian⁴ in 1983 and on similar analysis and experiments performed at MIT. Recently an MIT gyrotron produced a pulsed output of 645 kW at 140 GHz using a $TE_{15,2,1}$ cavity.⁵

For the 140 GHz gyrotron development at Varian the emphasis has always been on operation at long pulse (100 msec) or CW. The limitations on power output in that case are generally caused by excessive heat in some areas, such as the interaction cavity or the output window. If operation at short pulse length and lower duty factor is of interest, the power output can generally be increased significantly. For example, the 100 kW CW gyrotron performs well at 200 kW output with 1 msec pulse length.

EXPERIMENTAL RESULTS AT THE 100-200 kW LEVEL

The first experimental 140 GHz gyrotron was successfully tested up to a CW power level of 75 kW and a pulsed power level of 100 kW³. It employed a simple,

tapered TE_{03} interaction cavity with the hollow electron beam situated on the second radial maximum of the electric field in the cavity. Mode competition served to limit the output powers and efficiencies obtainable with the tube. The design of the first tube adequately handled the significant thermomechanical stresses present during the CW operation up to 75 kW. Fluctuations in the temperature of the output window, caused by the phasing of the various modes comprising the microwave output, led to the decision to limit CW powers to 75 kW. The mode competition limitations were addressed in the second experimental 140 GHz tube by replacing the simple, tapered TE_{03} cavity with a complex TE_{02}/TE_{03} cavity. To avoid the window temperature fluctuations, the taper between the cavity and the collector was designed to eliminate conversion of the desired TE_{03} output mode to other TE_{0n} modes. Other elements of the design of the second 140 GHz tube, including the design of the electron gun, remained the same as in the first tube and have been discussed in detail in earlier publications^{2,3}.

During pulse tests on the second 140 GHz tube, a series of parameter variation studies were carried out to investigate regions of stability in the desired TE_{02}/TE_{03} complex cavity mode and determine the degree to which the complex cavity would eliminate the mode competition observed on the first experimental tube which had employed a simple, tapered TE_{03} cavity. Most of the pulse tests were performed at a repetition rate of 10 pps with pulse durations of 1.0 ms.

In Figure 1, we show measurements of the output power in the desired TE_{03} mode (determined by output frequency) for variations of the beam voltage over the range 50 kV to 80 kV for four different values of cavity magnetic field and a constant beam current of 6.0 A. Power levels as high as 150 kW and as low as 1 kW were measured for these parameter variations. In Figure 2, we have plotted output power and efficiency as a function of beam current for a constant cavity magnetic field of 54.4 kG. At a beam current of 8.4 A, an output power of 200 kW was obtained with 30% efficiency.

In Figure 3, the variation of output power as a function of gun-anode voltage is shown for a beam voltage of 80 kV and a beam current of 8.4 A. At the optimum value of cavity magnetic field of 54.4 kG, the output power was variable from about 110 kW to 200 kW over a 500 V gun-anode voltage range. When the cavity magnetic field was detuned to 54.8 kG, output power could be varied from 10 kW to 150 kW over a gun-anode voltage range of 1.3 kV.

During tests at pulse durations of 100 ms, an output power of 150 kW was obtained at 27% efficiency using a beam voltage of 70 kV and a beam current of 8.2 A. The slightly lower efficiency during long-pulse operation (compared to 30% efficiency for similar

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FIGURE 1. OUTPUT POWER vs BEAM VOLTAGE FOR DIFFERENT VALUES OF CAVITY MAGNETIC FIELD DURING PULSE TESTS ON THE SECOND EXPERIMENTAL 140 GHz GYROTRON

FIGURE 2. OUTPUT POWER AND EFFICIENCY vs BEAM CURRENT DURING PULSE TESTS ON THE SECOND EXPERIMENTAL 140 GHz GYROTRON

parameter settings during short-pulse operation) was due to a droop in the gun-anode voltage during the 100 ns pulses.

For CW tests, all of the tube coolant flow circuits were monitored calorimetrically to measure rf losses in the various parts of the tube. In addition, the output window was monitored with an infrared imaging system to determine its temperature for various operating conditions. During the tests, a maximum output power of 100 kW was achieved under CW operating conditions at an efficiency of 27%. In Figure 4, we plot output power as a function of beam current. As indicated by the figure, 100 kW was obtained at a beam voltage of 60 kV and a beam current of about 6.1 A. While operating at 100 kW CW, the measured power losses in the cavity were 7.70 kW and power losses of 4.5 kW were measured in various other parts of the tube such as the beam tunnel, output window and collector seals.

If these rf losses are added to the output power, the resultant interaction efficiency was 30.5%. The peak temperature of the output window was 110°C. While varying the output power during the CW tests, the temperature of the output window varied correspondingly, indicating that the output mode purity was probably improved from that of the first tube where large temperature variations were observed for small changes in power³.

DESIGN OF A 1 MW GYROTRON

Interaction Cavity

The interaction cavity will consist of a simple, tapered, TE_{15,2,1} cavity, resonant at a frequency of 140 GHz. The loaded Q of the cavity will be between 350 and 500, which is consistent with efficiency and

FIGURE 3. OUTPUT POWER vs GUN-ANODE VOLTAGE FOR DIFFERENT VALUES OF CAVITY MAGNETIC FIELD DURING PULSE TESTS ON THE SECOND EXPERIMENTAL 140 GHz GYROTRON

FIGURE 4. OUTPUT POWER AND EFFICIENCY vs BEAM CURRENT DURING CW TESTS ON THE SECOND EXPERIMENTAL 140 GHz GYROTRON

ohmic loss considerations. Other important factors in the cavity design will include output mode purity and back-rf leakage. The cavity output mode must be relatively pure to enable efficient conversion of the whispering-gallery-mode output into a configuration which is desirable for output power end-use. Back-rf leakage must be minimized to facilitate the beam tunnel design and prevent disruptions in the electron gun.

To explore possible competing modes the start oscillation of nearby cavity modes was calculated and the results are shown in Figure 5. For this calculation we assumed that all cavity modes have a Q of 400 and we assumed a beam voltage of 70 kV with $v_1/v_2 = 2$, where v_1 and v_2 are perpendicular and parallel components of electron velocity. The results show that the $TE_{15,2,1}$ mode has the lowest starting current of any nearby mode, and that there is room to operate on the low-magnetic-field-side of the curve where high efficiency operation will occur.

Electron Gun

The electron gun for the 1 MW tube design will be essentially the same gun developed for the MIT megawatt experiments. The gun is designed for operation with a beam voltage of 80 kV and a beam current up to 50 A.

The nominal radius of the beam in the interaction circuit coincides with the inner electric field maximum of the $TE_{15,2,1}$ mode at 140 GHz. The basic design parameters for the gun are summarized in Table 1.

Table 1
Basic Design Parameters

Beam Voltage	80 kV
Operating Current	35 A - 50 A
Cavity Magnetic Field	5.55 T
Cavity Average Beam Radius	0.53 cm
Cavity v_1/v_2	2
$\Delta v_1/v_1$	<5%
Beam Thickness	0.59 mm
Magnetic Compression	30

Computer simulations were performed to verify the performance of the gun. Figure 6 shows electron trajectories plotted in the R - z plane. Figure 7 shows the effect of gun first anode voltage on the velocity ratio, v_1/v_2 , and on the spread in perpendicular velocity, $\Delta v_1/v_1$. A beam current of 35 A was used in the calculation. Near the design value of $v_1/v_2 = 2$, the calculated velocity spread is less than about 5%.

FIGURE 5. STARTING CURRENT vs MAGNETIC FIELD FOR THE $TE_{15,2,1}$ MODE AND NEIGHBORING COMPETING MODES. ALL MODES HAVE A LOADED Q OF 400.

FIGURE 6. ELECTRON TRAJECTORY SIMULATION

Simulations with 50 A of beam current produced similar results except that velocity spread was typically a factor of 2 larger. A perpendicular velocity spread of 10% should have only a minor effect on gyrotron oscillator efficiency.

Output Coupler

The first experimental 1 MW CW tube will employ standard output coupling where the electron beam collector also serves as the output waveguide.

The uptaper and collector designs will be similar to those employed in the present 140 GHz test vehicles, but the length and diameter of the collector will be somewhat greater. This will allow the safe collection of the higher power electron beam in the proposed 1 MW tube. The uptaper between the cavity and the collector will be designed to minimize undesired mode conversion while maintaining reasonable tube length. A nonlinear taper will be utilized to fulfill these requirements. Collector diameter and length will be determined from an analysis of collector electron trajectories. To facilitate the collector cooling design, power

densities will be held to $< 1 \text{ kW/cm}^2$. The collector design must also be consistent with the output window diameter design, which is chosen by different criteria.

Output Window

The output window on the first tube will be a double-disc, face-cooled design similar to that used in current 140 GHz tubes except that the cooling will be optimized for the whispering gallery mode pattern. Calculations indicate that temperature rise and the resulting mechanical stress are very important concerns for CW operation.

CONCLUSIONS

Tests of existing 140 GHz gyrotrons indicate that practical designs are available to produce power output of 100 kW CW and 200 kW with 1 msec pulse length. Calculations indicate that 1 MW CW output of 140 GHz is feasible. High power density in the cavity wall and high temperature of the output window are important concerns in the MW design.

FIGURE 7. V_1/V_0 AND $\Delta V_1/V_1$ SENSITIVITY TO MOD-ANODE VOLTAGE

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