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DESIGN CONSIDERATIONS FOR A 100 KW CW, 140 GHz GYROTRON OSCILLATOR

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ABSTRACT

A gyrotron oscillator capable of generating 100 kW of CW power is currently under development at Varian. The tube is being designed for operation in the TE_{033} cavity mode with the electron beam located at the second radial electric field maximum in the cavity. The electron beam will be produced by a magnetron injection gun and the 56 kG magnetic field required for 140 GHz operation will be provided by a superconducting magnet. Initial design calculations for the important elements of the tube are reported and the various technology issues of the tube design are discussed.

INTRODUCTION

The Varian 140 GHz gyrotron is being developed as part of the National Gyrotron Program with the goal of providing sources for use in electron cyclotron resonance heating (ECRH) in magnetic confinement fusion devices. Previous gyrotron development programs at Varian have resulted in tubes capable of generating power levels of 200 kW CW at 28 GHz and 60 GHz (1,2). In addition, 200 kW, 100 ns pulse tubes at 51 GHz, 60 GHz and 70 GHz have been delivered to various fusion laboratories, and 200 kW CW tubes at 35 GHz and 56 GHz are currently being developed (2).

The primary goal of the program is to produce 140 GHz tubes which generate power levels of 100 kW CW. In addition, it is important that the output of the tubes consists of a single mode. This enables efficient conversion of the microwave power into the mode most desirable for transmission to and injection into the experimental vessel. Finally, tubes must be stable and reliable, since they may be used in a reactor environment.

The basic tube design of the 140 GHz gyrotron is similar to tubes developed at lower frequencies. A series of 140 GHz gyrotron experiments at the Massachusetts Institute of Technology (3) have also provided useful information for the present 140 GHz design. In the following, we summarize the basic design of the major elements of the 140 GHz gyrotron.

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GYROTRON DESIGN

The design of the tube is centered around an interaction which is resonant in the TE_{033} cavity mode at 140 GHz. The electron beam will be located at the second radial maximum in the cavity. The choice of the second radial maximum, rather than the first maximum, was made 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 out the end of the cavity into the output waveguide and exits the tube through a vacuum window. The 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_{033} cavity, they propagate in the TE_{03} mode in circular waveguide. This mode is easily converted into the TE_{03} circular waveguide mode for long distance transmission.

Interaction Circuit

Simple Cavity. The first type of cavity to be tested during the 140 GHz program will be a simple, tapered TE_{033} cavity. It will be similar in design to the ones used in many previous gyrotrons (4).

One of the major problems in using this type of higher order mode cavity is mode competition with neighboring cavity resonances. For the TE_{033} mode, the major competing mode is the TE_{031} mode. This aspect is shown graphically in Figure 1, where the three solid-line curves represent the small-signal start oscillation current as a function of magnetic field for the TE_{031} , TE_{033} and TE_{035} cavity modes in a 140 GHz tapered cavity design. The dashed lines superimposed on the plot are the results of large-signal calculations for the TE_{033} mode alone. Each dashed line shows the variation of beam current vs magnetic field for a constant output power. The optimum efficiency point for a given power level is located at the minimum of each of the curves. Here we see that the TE_{033} mode has a lower starting current than the TE_{031} mode for magnetic fields where the TE_{033} mode has the highest efficiency. This indicates that mode competition with the TE_{031} mode may limit the efficiency of the TE_{033} mode.

Also of interest in Figure 1, is the fact that the optimum efficiency for most of the power levels

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Figure 1. Small signal starting current vs magnetic field for the TE_{021} mode and the competing TE_{031} and TE_{041} modes. Also shown are the results of large signal calculations for the TE_{021} mode showing beam current vs magnetic field for different power levels. Both small and large signal calculations were performed for a beam voltage of 50 kV and $a = 2$.

shown lies outside of the TE_{021} starting current curve. This would indicate that access to the high efficiency region of parameter space is limited, since oscillation must begin in the small-signal regime.

Fortunately, two additional pieces of information must also be taken into account when discussing mode competition and access to the high efficiency regime. First, in CW operation, it is possible to turn on the oscillation in an accessible region of parameter space, with no mode competition, and then tune the parameters to enter the high efficiency regime. In this case, the starting conditions are modified by the presence of the oscillation, and allow access to the previously inaccessible regions of parameter

Figure 2. Efficiency vs output power level for TE_{021} simple cavity design for different beam voltages. The magnetic field is chosen to optimize the efficiency at each power level.

space. Second, as a tube is turned on in pulse operation (or when parameters are varied in CW operation), different values of a are present as a function of time. This also allows access to the high efficiency region of parameter space with reduced mode competition (5,6).

Another problem in high frequency gyrotron cavities is the safe dissipation of power deposited in the cavity walls due to ohmic losses. To minimize this effect, low beam voltage is desirable. Use of low beam voltage reduces the strength of the rf electric field, which is required to optimize the interaction between the electron beam and cavity fields. Lower electric fields in the cavity imply lower power densities on the cavity walls. This is shown in Figure 2, where we plot efficiency vs output power for different beam voltages for a simple TE_{021} cavity design. Here we see that the higher the voltage, the higher the power level at which optimum efficiency is obtained.

Complex Cavity. The second type of cavity to be tested during the 140 GHz gyrotron program is a TE_{021}/TE_{031} step or complex cavity. This type of cavity still suffers from the problem of ohmic heating in the cavity walls but the problem of mode competition is reduced. A schematic diagram of a TE_{021}/TE_{031} cavity design, showing lines of constant rf magnetic field, is shown in Figure 3.

Figure 3. Example of a TE_{021}/TE_{031} complex cavity.

In this type of cavity, the electron beam is bunched in the first portion of the cavity, where mode competition is less than in the higher order mode output cavity. Energy is then extracted from the pre-bunched beam in the larger cavity. This type of cavity has been successfully employed in TE_{011}/TE_{011} (1) and TE_{011}/TE_{011} (7) configurations. However, no experiments have yet been performed where the mode in the first part of the cavity is of higher order than TE_{011} . This concept will be tested early in the 140 GHz program.

Electron Gun

The electron gun for the 140 GHz gyrotron will be a magnetron injection gun, similar to those used on previous gyrotrons developed at Varian. In addition, Varian has recently designed and constructed two magnetron injection guns for 140 GHz gyrotron experiments at the Massachusetts Institute of Technology (8). Those experiments investigated gyrotron operation at a frequency of 140 GHz, using a TE_{011} interaction cavity, with the electron beam located at the second radial electric field maximum in the cavity. Since the MIT experiments employed the same basic circuit configuration and frequency as those to be used in the present 140 GHz gyrotron development effort, the MIT gun designs served as the starting point for the gun design for the present 140 GHz gyrotron.

Both of the original MIT guns were designed for operation at 65 kV, 5 A. For the present 140 GHz program, however, lower voltage operation is desired, as discussed earlier. A second requirement, more critical in the present 140 GHz CW gyrotron than in the MIT short-pulse experiments, is the need to minimize beam thickness, or spread, in guiding center radii in the beam. Thinner beams reduce the possibility of interception in the beam tunnel. This restriction favors designs with lower cathode angles (the two MIT designs had cathode angles of 15° and 25°); and cathode leading should be as high as possible without sacrificing cathode reliability or gun performance. These considerations led to a new design, similar to the MIT gun with a 15° cathode angle.

A computer simulation for the preliminary electron gun design is shown in Figure 4. A list of the performance parameters for this preliminary gun design are shown in Table 1.

Table 1
Performance Parameters for 140 GHz
Gun Design

Beam Voltage	50 kV
Gun-Anode Voltage	14-15 kV
Beam Current	8 A
Cathode Loading	6.4 A/cm ²

$$a \approx \frac{v_z}{v_0} \text{ (velocity ratio)} \quad 1.5 - 2.0$$

$$\frac{\Delta v_z}{v_z} \quad \leq \pm 3\%$$

Beam Radius at Resonator	0.182 cm
Beam Thickness at Resonator	$0.038 \pm 3 r_L$ (for $a=2$)

In computer simulations leading to the design shown in Figure 4 and summarized in Table 1, beam characteristics at the cavity were deduced by adiabatically scaling the results of the simulation soon after the beam had entered the beam tunnel/main anode region. To further verify the performance of the gun, the simulation was continued all the way to the cavity. In Figure 5, we show the electron trajectories as they enter the cavity. We note that the laminar nature of the beam, present in Figure 4, has completely disappeared in Figure 5. In addition, the potential depression of the beam as it entered the cavity is indicated by the behavior of the 49.5 kV equipotential line at the entrance of the cavity. The potential depression of the beam from the grounded tube wall increased from 0.5 kV in the beam tunnel to 1.5 " inside the cavity.

The simulation of the beam all the way to the cavity indicated that a value of $a \approx 2$ could be achieved without mirroring any of the electron trajectories. This verified the earlier adiabatic scaling results, though a small nonadiabatic increase in the perpendicular velocity spread was noted.

Output Taper, Collector and Window

As mentioned earlier, the output waveguide from the cavity also serves as the electron beam

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Figure 4. Computer simulation of preliminary 140 GHz electron gun design.

Figure 5. Final segment of 140 GHz electron gun computer simulation showing the entrance of the beam into the Tl031 cavity.

collector. Since the collector must be capable of dissipating the full CW beam power of approximately 400 kW, an up taper between the cavity and the collector is required. The up taper for the 140 GHz tube must be designed to limit conversion of the Tl₀₃₁ output mode to other modes, but not be too long. Various nonlinear tapers are currently being investigated to satisfy these criteria. A preliminary design has a calculated mode purity of about 97% in the desired Tl₀₃₁ mode.

The collector diameter for the 140 GHz tubes will be 2.5 inches, the same as that of the 50 GHz, 200 kW CW tubes (1). This diameter should be sufficient to allow the safe collection of the spent electron beam, though small magnet coils may be required along the collector to evenly distribute the impinging electrons.

The output window will also have a 2.5-inch diameter so that no down taper is required between the window and the collector. The window will be a double-disc window, with face cooling between the ceramic discs provided by a low-loss dielectric fluid. The major concern in designing the 140 GHz window is thermomechanical stress in the window. The thermomechanical stresses are caused by the combination of thermal stresses, due to the rf losses in the ceramics, and the static stresses, created by the pressure of the coolant fluid on the ceramics (especially on the vacuum side window). This is being investigated for the 140 GHz window by using computer codes which simulate the electrical and mechanical environment of the window to optimize the design.

Magnet

The superconducting magnet for the 140 GHz gyrotron must be capable of providing a 90 - 56 kG magnetic field in the cavity region. Designs with two and three main magnet coils are being considered. The magnetic field in the gun region will be regulated by two smaller superconducting coils which will either subtract or add to the field of the main coils present at the gun.

SUMMARY

The development of the 140 GHz, 100 kW CW gyrotron relies heavily on the technological advances made during previous successful development programs at lower frequencies. The increased frequency complicates the design of many of the important elements of the gyrotron. Some of the critical issues addressed in the present tube design include: mode competition with the desired Tl₀₃₁ operating mode in the cavity, high power densities on the cavity walls due to ohmic losses, electron beam transmission through the beam tunnel,

mode conversion in the up taper between the cavity and the collector, and thermomechanical stresses on the output window. The achievement of the objectives of the 140 GHz gyrotron effort will represent a significant advance in the state-of-the-art of high average power microwave tubes.

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