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MILLIMETER-WAVE, MEGAWATT GYROTRON DEVELOPMENT FOR ECR HEATING APPLICATIONS

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ABSTRACT

To address the electron cyclotron heating requirements of planned fusion experiments such as the International Thermonuclear Experimental Reactor (ITER) and the Compact Ignition Tokamak (CIT), Varian is developing gyrotrons at frequencies ranging from 100-300 GHz with output power capabilities up to 1 MW CW. Experimental gyrotrons have been built at frequencies between 100-140 GHz, and a study program has addressed the critical elements of designing 280-300 GHz gyrotrons capable of generating CW power levels up to 1 MW. Initial test vehicles at 140 GHz have utilized TE_{15,2,1} interaction cavities, and have been designed to generate short-pulse (up to 20 ms) power levels of 1 MW and up to 400 kW CW. Recently, short-pulse power levels of 1040 kW at 38 % efficiency have been obtained and average powers of 200 kW have been achieved. Long-pulse operation has been extended to pulse durations of 0.5 seconds at power levels of 400 kW. Gyrotron oscillators capable of generating output powers of 500 kW CW at a frequency of 110 GHz have recently been designed and a prototype is currently being tested. Design work for a 1 MW CW gyrotron at 110 GHz, is in progress. The 1 MW CW tube will employ an output coupling approach where the microwave output is separated from the microwave output.

1. INTRODUCTION

Gyrotron oscillators have been effectively employed in heating magnetically-confined plasmas, at the electron cyclotron resonance (ECR) frequency, in a variety of fusion experiments.[1] In these experiments, gyrotrons with long-pulse or CW output powers of a few hundred kilowatts have been utilized at frequencies up to about 100 GHz. However,

ECR heating in large, reactor-size fusion experiments, will require total input microwave power levels of 10-100 MW at frequencies ranging from 100 GHz to 300 GHz.[2]

To address this need, Varian is developing gyrotrons capable of generating power levels of 1 MW CW at frequencies in the range 100 GHz to 140 GHz. The basic design approach followed in the current gyrotron development program is significantly different than that of earlier efforts at lower frequencies and power levels. While most previous tubes were designed to generate output power in the TE_{0n} or circular-electric class of waveguide mode,[3,4] the current work utilizes TE_{mn} whispering-gallery modes where $m \gg n$. In contrast to circular-electric modes, energy stored in a whispering-gallery-mode cavity is concentrated near the walls of the cavity, thereby requiring a relatively large-diameter electron beam for efficient interaction. The choice of whispering-gallery modes over other classes of interaction circuits is based on an intricate set of design trade-offs that include considerations of mode competition, ohmic losses in the cavity, efficiency, potential depression of the electron beam, and electron gun design.[5] Experimental research with whispering-gallery-mode gyrotrons is also being carried out at MIT,[6] Toshiba,[7] and in the Soviet Union.[8]

In working toward the 1 MW CW output power goal, several experimental vehicles will be constructed and tested to verify the design of the important elements of the gyrotron. The first two tubes in the program have been designed to generate short-pulse power levels of 1 MW and CW or long-pulse (> 1 second) power levels up to 400 kW at a frequency of 140 GHz. The testing of these tubes serves to validate the basic design of the electron gun and interaction circuit. In addition, operation at CW or long-pulse powers up to 400 kW provides useful information concerning whispering-gallery-mode operation at high-average-power levels.

The first experimental tube underwent a series of four tests, the final three following rebuilds of the tube that incorporated various design modifications indicated in the preceding test. During these tests a maximum peak power level of 820 kW and a maximum average power of 80 kW were obtained in the desired whispering-gallery mode at a frequency of 140 GHz. Pulse durations of 60 ms were obtained for output

powers of 400 kW.[9] A photograph of the first experimental tube with the 140 GHz superconducting magnet is shown in Figure 1.

Figure 1. Photograph of first experimental 140 GHz gyrotron and superconducting magnet.

The second experimental tube has been tested and rebuilt twice. The second rebuild of this tube is currently being tested. The second tube was designed to test several new features aimed at overcoming some of the performance limitations of the first experimental tube. Salient features of the second experimental tube and a review of the experimental results to date will be discussed below.

CW gyrotron oscillators capable of generating 500 kW at a frequency of 110 GHz have recently been designed. These tubes will also employ whispering-gallery-mode cavities. The first experimental vehicle has been constructed and is currently being prepared for test.

Future test vehicles are now being designed to achieve full 1 MW CW operation. To be consistent with planned ECR heating experiments in the U.S., the design frequency has been changed from 140 GHz to 110 GHz. The basic philosophy underlying the 1 MW CW work is to extend the design of the 140 GHz, 1 MW pulsed, 400 kW CW test vehicles where possible and add new approaches or capabilities where necessary to achieve reliable 1 MW CW operation.

In the following we summarize the important design features of the second experimental gyrotron, review the results of the first two test iterations on the second tube, and discuss recent test results obtained during the third test sequence on the tube. We will summarize the design of the 110 GHz, 500 kW CW gyrotrons and discuss the major design issues for the first 1 MW CW experimental gyrotron.

2. DESIGN OF SECOND EXPERIMENTAL GYROTRON

The design concept of the second experimental 140 GHz, 1 MW gyrotron is similar to that of the first experimental tube.[9] The design is based on the interaction between a hollow electron beam provided by a magnetron injection electron gun and a simple, tapered cavity designed to generate power in the $TE_{15,2,1}$ mode at 140 GHz. The average radius of the electron beam in the interaction region coincides with the position of the first radial maximum of the electric field in the cavity. Computer simulations of the performance of the electron gun predict perpendicular velocity spreads of less than 5% for operation at a perpendicular to parallel velocity ratio of two. The nominal beam voltage and current for the gun

are 80 kV and 35 A, respectively, though operation at beam voltages of 90-100 kV and beam currents up to 50 A is possible. The magnetic field in the cavity and gun regions is provided by a superconducting magnet. For operation at 140 GHz, a magnetic field of 56 kG is required in the interaction region. The magnetic field in the electron gun is about 2.2 kG.

Output power from the cavity travels through the collector and out of the gyrotron through a double-disc, face-cooled window. The up and down tapers in the collector region are designed to preserve the purity of the generated $TE_{15,2}$ mode. The spent electron beam follows the diverging magnetic field lines out of the cavity and is deposited on the walls of the collector. Several magnetic field coils are employed in distributing the spent electron beam evenly along the collector.

New features in two areas of the tube, aimed at alleviating various problems experienced during the tests of the first experimental tube,⁹ have been incorporated into the design of the second tube. Refinements to the beam tunnel have been included in the new tube design to further stabilize this region against spurious oscillations. Several modifications to the collector have been made to detect and prevent the type of damage sustained in the last set of tests on the first tube.[9]

3. TEST RESULTS ON SECOND EXPERIMENTAL GYROTRON

3.1 First test of second experimental gyrotron

During the first series of tests on the second experimental 140 GHz gyrotron, a peak output power of 940 kW was obtained at an efficiency of 35 %. Long-pulse and high-average-power tests were not performed on the tube during this test sequence due to arcing in the cavity region of the tube. The arcing was caused by high local gas pressures generated by various materials used in constructing the beam tunnel adjacent to the cavity.

3.2 Second test of second experimental gyrotron

Following the first test sequence on the second experimental tube, the tube was disassembled and reassembled with a new beam tunnel. The

material that was responsible for the outgassing that led to arcing in the interaction cavity was eliminated from the design.

The second series of tests on the second experimental tube were aimed at achieving high-average-power operation. Following initial short-pulse, parameter variation studies, the tube was aged to an average output power of 160 kW at a peak power of 345 kW. A repetition rate of 120 pps and a pulse duration of 3.9 ms were used in this test.

The second test sequence was cut short by a vacuum leak in the tube that occurred during a time when the tube was not in operation. Subsequent analysis of the tube indicated that the leak was in a cooling line and not related to the operation of the tube in any way.

3.2 Third test of second experimental gyrotron

Following the examination of the tube after the second test sequence, the defective cooling lines were replaced and the tube was reassembled for test. The third series of tests were begun in June 1990 and are still in progress.

During short-pulse operation, output powers up to 1040 kW at 38 % efficiency were obtained. Parameters for operation at 1040 kW are listed in Table I.

Table I
Parameters for 1040 kW operation during
Third test of Second Experimental Gyrotron

FREQUENCY	140.155 GHz
OUTPUT POWER	1038 kW
PULSE DURATION	0.5 ms
REPETITION RATE	10 pps
BEAM VOLTAGE	80 kV
BEAM CURRENT	34.3 A
OUTPUT EFFICIENCY	38 %
MEASURED LOSSES	138 kW
TOTAL GENERATED POWER	1176 kW
INTERACTION EFFICIENCY	43 %

A plot of output power and efficiency as a function of beam current is shown in Figure 2. We note that the efficiency was relatively flat over the range of beam currents shown in the figure. Efficiency was optimized for each value of beam current by adjusting the cavity magnetic field and the gun-anode voltage (that controls the perpendicular-to-parallel velocity ratio, α). In general, the gun-anode voltage was increased to the point where current was drawn to the gun-anode electrode.

Figure 2. Output power and efficiency as a function of beam current during third test of second experimental gyrotron.

In Figure 3 we plot the value of α estimated from electron gun simulations for each experimental point shown in Figure 2. As noted on Figure 3, the maximum gun-anode voltage without gun-anode current generally decreased with current. This effect is thought to be due to increasing velocity spread with beam current.[10] The increased velocity spread leads to electron beam mirroring at lower values of α or gun-anode voltage. In addition to the lower achievable value of gun-anode voltage, the decrease in α with beam current is also due to the effects of increased space charge in the beam formation region of the electron gun.

Figure 3. Estimated alpha (α) as function of beam current for experimental points shown in Figure 2.

In Figure 4 we have plotted the same experimental efficiencies as well as those predicted by self-consistent, large-signal calculations for $\alpha = 1.5$ and 2.0. (The theoretical efficiencies have been adjusted to include the effects of rf losses measured in the tube.) These results show that there is

Figure 4. Comparison of theoretical efficiencies as a function of beam current with results obtained during third test of second experimental gyrotron.

good agreement between the observed and predicted efficiencies when the estimated value of α for each experimental point (see Figure 3) is used in the comparison.

At output powers of around 400 kW, short-pulse operation has been extended to duty factors of nearly 50 %, resulting in average output powers of 200 kW. Parameters for 200 kW average power operation are listed in Table II. The output efficiency for 200 kW average power operation was not optimized. Instead, tube parameters were adjusted to enable operation in a regime where tube performance was relatively insensitive to changes in the settings of various parameters (i.e. gun-anode voltage, beam current, cavity magnetic field, beam voltage, etc.).

Table II
Parameters for 200 kW average power operation during
Thirld test of Second Experimental Gyrotron

FREQUENCY	139.837 GHz
OUTPUT POWER	412 kW
PULSE DURATION	4.0 ms
REPETITION RATE	120 pps
DUTY FACTOR	48 %
AVERAGE POWER	198 kW
BEAM VOLTAGE	80 kV
BEAM CURRENT	17.2 A
OUTPUT EFFICIENCY	30 %
MEASURED LOSSES	61 kW
TOTAL GENERATED POWER	473 kW
INTERACTION EFFICIENCY	34 %

Long-pulse operation has been extended to pulse durations of 500 ms at output powers of 350-400 kW. Operating parameters for 380 kW, 500 ms operation are summarized in Table III. Again, these tests were not carried out at optimum efficiency in order to remain at conditions that enabled operation over a wide range of parameter settings. During long-pulse operation, the frequency was monitored as a function of time during the pulse. This was accomplished using a harmonic-mixer based system, similar to one developed at KFK.[11] The intermediate frequency (IF)

produced in the harmonic mixer is directly displayed as a function of time on an HP 5371A Frequency and Time Interval Analyzer. Observed changes in the IF translate directly into changes in the gyrotron output frequency.

Table III
Parameters for 500 ms pulse operation during
Third test of Second Experimental Gyrotron

FREQUENCY (end of pulse)	140.066 GHz
OUTPUT POWER	384 kW
PULSE DURATION	500 ms
REPETITION RATE	0.01 pps
DUTY FACTOR	0.5 %
BEAM VOLTAGE	80 kV
BEAM CURRENT	17.1 A
OUTPUT EFFICIENCY	28 %

An example of the frequency changes present during a 500 ms pulse are shown in Figure 5. As indicated in Figure 5, the frequency typically

Figure 5. Frequency vs. time within a 500 ms pulse at 380 kW output power during third test of second experimental gyrotron.

takes a 50-100 MHz downward jump after the first 30-60 ms, then decreases quite slowly (about 2 MHz per 100 ms) during the remainder of the pulse. Variations in the frequency are attributed to thermally induced changes in the cavity and output window.

Further long pulse tests on the second experimental tube are still in progress. The current test plan is to extend long-pulse operation at 400 kW to pulse durations in excess of 1 second.

4. 110 GHz, 500 kW CW GYROTRON DESIGN

Gyrotrons capable of generating 500 kW CW at 110 GHz have been designed for ECR heating experiments. The tubes use the same basic approach as the 140 GHz, 1 MW pulsed, 400 kW CW experimental tubes described above, including the use of the $TE_{15,2,1}$ mode in the cavity. Major tube elements such as the electron gun, beam tunnel and cavity are somewhat larger in size as a result of the lower frequency. Power densities in the cavity for operation at 500 kW are somewhat lower than in the 140 GHz tube operating at 400 kW, as a result of the increased cavity size and the reduced ohmic losses at the lower frequency. (For a given mode, output power and loaded Q, power densities in the cavity scale as frequency to the $-5/2$ power.)

The diameter of the collector remains at five inches, but the collector length has been increased by 18 inches to accommodate the desired 25 % increase in power handling capability. The output window is virtually the same as the 3.5-inch diameter, double-disc design employed on the 140 GHz tubes, but is tuned for 110 GHz operation. Peak temperatures and stresses in the window for 500 kW operation at 110 GHz are similar to those predicted for 400 kW operation at 140 GHz.

The first 110 GHz, 500 kW prototype tube has been constructed and is currently in the initial stages of test.

5. 1 MW CW DESIGN CONSIDERATIONS

In order to extend the capabilities of the present 140 GHz, 1 MW pulsed, 400 kW CW gyrotron design to full 1 MW CW operation at a frequency of 110 GHz, several elements of the tube require additional

design work. The critical areas include the interaction cavity, output coupler, electron beam collector, and output window. Below we review the current design approaches being considered for each of these areas for inclusion into the first 110 GHz, 1 MW CW test vehicles.

5.1 Interaction cavity

In the interaction cavity, the ohmic losses in the cavity walls result in relatively high heat fluxes that must be removed by the cooling design. The present 140 GHz design, based on the TE_{15,2,1} mode, should be capable of withstanding the heat fluxes present at CW power levels of between 400 and 500 kW. To reach 1 MW CW at 110 GHz would require only modest improvements to the 140 GHz, lower power design, due to the larger cavity size and increased ohmic Q present at the lower frequency. However, it has been decided to reduce the cavity power density to a level that is handled routinely in earlier production gyrotrons. This will be accomplished by using a higher-order, whispering-gallery mode in the cavity. A tentative cavity design, employing the TE_{22,2,1} mode, has been chosen.

5.2 Output Coupler and Electron Beam Collector

The problems of output coupling and electron beam collection are interrelated. For full 1 MW CW operation, the electron beam collector must be significantly larger than the present design, that also serves as the output waveguide for the generated microwave power. Since mode conversion considerations preclude use of larger diameter collectors (without lengthening the tube significantly), methods of separating the electron beam from the microwave output are highly desirable. Two possible scenarios are currently being considered in addressing this problem.

5.2.1 Radial beam extraction. One method of separating the electron beam from the rf output provides for the radial extraction of the electron beam through a slot in the output waveguide, while the generated microwave power continues straight through the tube as in the classic design employed in most previous gyrotrons.

Of importance in this approach are the guidance of the electron beam through the gap introduced into the waveguide, mode conversion resulting from the gap, and rf leakage through the gap. A series of tradeoff analyses is currently being carried out to try to minimize these detrimental effects and allow an efficient electron beam/rf separation to take place.

5.2.2 Quasi-optical output coupler. The second approach allows for the radial extraction of the microwave power while the electron beam continues straight through to a large-diameter collector. This approach has been successfully used in Soviet gyrotrons,[8] with the incorporation of a quasi-optical coupler.

Quasi-optical techniques under development at Varian for output coupling include a modified form of the Vlasov coupler technique.[12] The main issues of any output coupling technique are the delivery of microwave power from the cavity to the external world and the delivery of that power in a useable form for highly efficient power transmission. These tenets are actually applicable, whether the coupler is internal or external to the gyrotron. Varian has set a goal to deliver 95% of the available power with typically a TEM₀₀ mode purity of 95%. The question of determining mode purity should be addressed by fitting the measured data with a basis set of TEM modes and a final demonstration of low-loss transmission along a quasi-optical or a corrugated transmission line.

The simple analysis of the Vlasov coupler, see Figure 6, involves the propagation of a rotating whispering-gallery mode in circular waveguide characterized by a bounce angle, θ , with respect to the axis. Azimuthally, the waves are propagating between the wall and a caustic determined by $R[\cos(m/x'_{mn})]$ where R is the waveguide radius, m is the azimuthal mode number and x'_{mn} is the n^{th} root of $J'_m(x) = 0$. Assuming the proper helical cut for the rotating whispering-gallery mode, the radiation pattern can be represented by geometrical optics as shown in Figure 6. The azimuthal pattern ranges from an angle α to $-\alpha$ ($\alpha = \arccos(m/x'_{mn})$). The straight edge is the launching edge. The width of the aperture window is the distance from wall to the caustic. Typical experimental results are that about 85% of the power is directed towards the region specified by geometrical optics after one or two mirrors. Mirrors serve to correct much of the radiation pattern and transport it through the magnet bore and out of the gyrotron. However, high-power transmission with high efficiency

and good mode purity for further transmission have not been verified simultaneously.

Figure 6. Schematic diagram of standard helical coupler showing geometrical optics representation.

Techniques to improve the Vlasov coupler include the modification of the launching edge by means of a curved lip or visor.[13,14] Another technique is to modify the helical cut to properly account for the path of the propagating plane waves in the waveguide.[14] Still another technique is to propagate a hybrid mode by using a corrugated circular guide as the coupler.[15]

The approach taken at Varian is to gradually transform the effective simple aperture gently by means of a horn or wing structure. The mechanical support for such a structure can be achieved by utilizing an option mentioned by Vlasov, et al.,[12] in which the region of the helical cut not intercepting the simple geometrical optic radiation pattern can still be the original wall of the cylindrical waveguide. The treatment of the helical coupler now as an aperture with a horn or wings (2,3, or 4 sides) leads to a simple effective aperture transition, see Figure 7. By properly shaping the size of the aperture, edge diffraction is also reduced. Control of the azimuthal spread of the horn or wings will also increase the gain of the coupler. This is advantageous for controlling the size of the mirrors. In fact, by controlling the shape of the horn for a plane parallel wave, this

structure can be closed and incorporate a window of rectangular cross section. The resultant highly overmoded rectangular waveguide can propagate a pure or mixed mode. The horn or converter structure can be corrugated for hybrid-mode propagation.

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Figure 7. Schematic diagram of aperture/wing coupler geometry.

Another advantage of this aperture-wing technique is in the application of step tuning. In step tuning the gyrotron, the gyrotron is operated in successive azimuthal mode numbers with a fixed radial mode number. Due to the fixed cavity size, the gyrotron is operated at stepped frequencies corresponding approximately to the cutoff frequency of the mode. These modes will then propagate to the coupler with the same bounce angle with respect to the axis. However, in a standard-type Vlasov coupler, slight mode variations will result in different azimuthal angular spreads. In the Varian aperture-wing coupler the azimuthal spread of the set of modes can be controlled. This, of course still requires that the modes from the cavity all have the same rotational direction.

Preliminary low-power, cold-test results, utilizing a $TE_{6,1}$ mode at 66 GHz are shown in Figures 8-10. Mirrors are not used in this set of measurements to illustrate the zeroth order improvement. Figure 8 shows

the azimuthal pattern for a helical coupler. Both the azimuthal (ϕ) and polar (θ) polarizations are shown. Figure 9 illustrates the improvement of the aperture-wing coupler. A slight dip near the central region in each of the data sets is probably due to input mode impurities, about 5 %, created during the generation of the whispering-gallery mode. A comparison of the helical coupler and an aperture-wing design is shown in Figure 10. Preliminary calculations show that width A, denoted on the pattern of the helical coupler, contains about 77% of the total I_ϕ power scan (76% including the I_θ polarization). Width B contains 97% of the power (96% with both polarizations). Width C, for the aperture-wing result, contains 98% (96% with both polarizations). Further improvements are expected with the proper helical cut at the base of the aperture. Work is continuing to map the phase front and to determine the mode purity, and power transmission after two mirrors.

Figure 8. Radiation pattern from a helical coupler showing both polarizations.

Figure 9. Radiation patterns for coupler with wings.

Figure 10. Comparison of radiation patterns from helical coupler and coupler with wings.

5.3 Output window

In any window design that is capable of passing 1 MW CW power levels, the major design limitations stem from the combination of thermal and mechanical stresses induced in the window. This environment calls for strong, low-loss window materials, and mechanical designs that minimize the static stresses due to window coolant and tube vacuum pressures and thermally induced stresses due to rf power absorbed by the window.

The specific geometry of the output window design depends on which output coupling approach is chosen. In the case of the quasi-optical output coupling approach, long, narrow rectangular windows can be made large enough to spread the output power from the tube sufficiently to allow safe operation. For the radial beam extraction configuration, enhanced versions of the existing circular, double-disc design may be employed. The present design is capable of 400 kW CW at 140 GHz, but calculations on new designs predict capabilities up to 1 MW CW at 140 GHz. For operation at 110 GHz, window losses are reduced significantly so that an even greater safety margin should exist.

6. CONCLUSIONS

The results obtained during the most recent tests performed on the second experimental 140 GHz gyrotron have essentially met the 1 MW pulsed and 400 kW CW or long-pulse goals of the initial test vehicles. These results also represent an important step in reaching the 1 MW CW goal of the current development program. Tubes based on the 140 GHz, 1 MW pulsed, 400 kW CW design will be useful in a variety of ECR heating applications in several present-day fusion experiments. Tests on the first 110 GHz, 500 kW CW prototype tube are now in progress. Design work is well underway in preparation for the fabrication of the first experimental 110 GHz, 1 MW CW gyrotron.

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