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UCRL-CR--106119

DE91 001681

NOV 01 1990

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OCTOBER 1990

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PROGRESS IN PRODUCING MEGAWATT GYROTRONS FOR ECR HEATING*

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Varian is carrying out the development of high-power, CW gyrotrons at frequencies ranging from 100-150 GHz for use in electron cyclotron resonance (ECR) heating of magnetically-confined plasmas. 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 40 kW at 35 % efficiency have been obtained and average powers of 200 kW have been achieved at peak powers of 400 kW. Long-pulse testing is currently underway. Initial tests have resulted in output power levels of 400 kW for pulse durations of 380 ms. Design work on 110 GHz, 500 kW CW gyrotron oscillators has recently been completed and a prototype tube has been assembled and is currently being tested. The design of a 110 GHz, 1 MW CW gyrotron, using a novel output coupling approach, is nearly complete. Fabrication of the first 1 MW CW experimental tube is in progress.

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 150 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 1 MW gyrotron oscillator is being developed under contract with Lawrence Livermore National Laboratory, operated by the University of California for the U. S. Department of Energy, under Prime Contract W-7405-eng-48.

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 80 ms were obtained for output powers of 400 kW.⁹

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 discussion 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 gyrotrons and discuss the major design features of the first 1 MW CW experimental gyrotron.

2. DESIGN OF SECOND TUBE

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 TUBE

3.1 First test

The first test of the second experimental 1 MW pulsed, 400 kW CW, 140 GHz gyrotron was carried out between September 1989 and January 1990. During these tests, a peak output power of 940 kW

was obtained at an efficiency of 85 %. A plot of output power and efficiency as a function of beam current is shown in Figure 1. Cavity magnetic field and gun-anode voltage (which controls the transverse energy in the beam) were optimized for maximum efficiency in this plot. The beam voltage was 80 kV.

FIGURE 1

Output power and efficiency versus beam current during first test of second experimental 140 GHz gyrotron.

We note that the efficiency remained relatively flat over the range of beam current covered in these tests. A plot of the experimental efficiency compared to the predictions of self-consistent, large-signal calculations is shown in Figure 2. The experimental efficiencies in Figure 2 have been adjusted to include the output efficiency shown in Figure 1 and measured rf losses in the tube (window, cavity, etc.) to enable comparisons with theory.

The electron gun generates an electron beam with a perpendicular-to-parallel velocity ratio (α) of between 1.5 and 2.0. The experimental results agree with theoretical predictions within the range of α , though it appears that the achievable α tends to decrease with increasing current. This decrease in α is due to space-charge in the electron beam and is consistent with electron beam simulations.

Long-pulse and high-average-power tests were not performed on the tube during this test

FIGURE 2

Experimental and theoretical efficiencies versus beam current for first test of second experimental 140 GHz gyrotron.

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

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 test sequence was carried out between March 1990 and May 1990. Rather than performing high-peak power tests on the tube, tests were aimed at achieving high-average-power operation. Following initial short-pulse, parameter variation studies, the tube was aged out 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. Losses of 44 kW were measured in the various internal portions of the tube (cavity, window, etc.). A list of the parameters used in achieving 160 kW average power is given in Table 1.

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.

Table 1

Parameters for 160 kW average power-second test

FREQUENCY	140.169 GHz
OUTPUT POWER	345 kW
PULSE DURATION	8.9 ms
REPETITION RATE	120 pps
DUTY FACTOR	48.8 %
AVERAGE POWER	161 kW
BEAM VOLTAGE	80 kV
BEAM CURRENT	16.2 A
OUTPUT EFFICIENCY	27 %
MEASURED LOSSES	44 kW
TOTAL GENERATED POWER	389 kW
INTERACTION EFFICIENCY	80 %

3.2 Third test

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.

Thus far the tube has been aged to pulse durations of 880 ms at output powers in excess of 400 kW. In addition, short-pulse, high-duty operation has been extended to average powers of 200 kW for peak output powers of over 400 kW. Operating parameters for 400 kW, 880 ms operation and 400 kW peak, 200 kW average power operation are given in Tables 2 and 3, respectively.

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

Table 2

400 kW, 880 ms operating parameters-third test

FREQUENCY	139.988 GHz
OUTPUT POWER	414 kW
PULSE DURATION	880 ms
REPETITION RATE	0.005 pps
DUTY FACTOR	0.19 %
BEAM VOLTAGE	80 kV
BEAM CURRENT	17.1 A
OUTPUT EFFICIENCY	80 %

Table 3

Parameters for 200 kW average power-third test

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	80 %
MEASURED LOSSES	61 kW
TOTAL GENERATED POWER	473 kW
INTERACTION EFFICIENCY	84 %

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

We are currently designing the first experimental gyrotron with the goal of achieving 1 MW CW operation at a frequency of 110 GHz. The present design calls for the use of the TE_{22,2,1} mode in the cavity.⁹ Using this mode, power densities in the cavity will actually be somewhat lower for 1 MW CW operation than in the 140 GHz tubes operating at 400 kW.

The major deviation from the previous, lower-power design will be in the area of the collector and output coupler for the tube. 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. In the first 1 MW CW tube, the method to be employed in 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 has been carried out to try to minimize these detrimental effects and allow an efficient electron beam/rf separation to take place.

The output window for the 1 MW CW tube at 110 GHz is still a double-disc, face-cooled design. It is somewhat larger than the 140 GHz design (or 110 GHz 500 kW design) and incorporates added mechanical features to reduce deleterious tensile stresses present during tube operation.

6. CONCLUSIONS

The results obtained during the three series of tests performed on the second experimental 140 GHz gyrotron 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. Design work is well underway in preparation for the fabrication of the first experimental 110 GHz, 1 MW CW gyrotron.

REFERENCES

1. R. Prater, V. S. Chan, and T. C. Simonen, "The Status of Electron Cyclotron Heating and Current Drive and the Role of DIII-D," GA Technologies Report No. GA-A18795, May 1987.
2. K. Kreischer, T. Grimm, A. Mobius, and R. Temkin, "The Design of Megawatt Gyrotrons for the Compact Ignition Tokamak," 13th Int. Conf. Infrared and Millimeter Waves, Conference Digest, 1988.
3. H. Jory, "Status of Gyrotron Development at Varian Associates," Proc. 4th Int. Symp. on Heating in Toroidal Plasmas, 1984, Vol. 2, pp. 1424-1430.
4. K. Felch, R. Bier, L. J. Craig, H. Huey, L. Ives, H. Jory, N. Lopez, and S. Spang, "Achievements in the CW Operation of 140 GHz Gyrotrons," 11th Int. Conf. Infrared and Millimeter Waves, Conference Digest, 1986, pp. 43-45.
5. K. E. Kreischer, B. G. Danly, J. B. Schutkeker, and R. J. Temkin, "The Design of Megawatt Gyrotrons," IEEE Trans. Plasma Science, 1985, Vol. PS-13, No. 6, pp. 364-378.
6. T. L. Grimm, K. E. Kreischer, W. C. Guss and R. J. Temkin, "Experimental Study of High Frequency, Megawatt Gyrotrons," 14th Int. Conf. Infrared and Millimeter Waves, Conference Digest, 1989, pp. 81-82.
7. T. Sugawara, et al., "500 kW Whispering Gallery Mode Gyrotron," 14th Int. Conf. Infrared and Millimeter Waves, Conference Digest, 1989, pp. 336-337.
8. Valery A. Flyagin and Gregory S. Nusinovich, "Gyrotron Oscillators," Proc. IEEE, 1988, Vol. 76, No. 8, pp. 644-656.
9. K. Felch, J. Feinstein, C. Hess, H. Huey, E. Jongewaard, H. Jory, J. Neilson, R. Pendleton, D. Pirkle, and L. Zitelli, "Design Considerations in Achieving 1 MW CW Operation with a Whispering-Gallery-Mode Gyrotron," International Electron Devices Meeting, Washington, D.C., Technical Digest, pp. 755-758.

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