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DESIGN CONSIDERATIONS IN ACHIEVING 1 MW CW OPERATION WITH A WHISPERING-GALLERY-MODE GYROTRON*

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ABSTRACT

Varian is developing high-power, CW gyrotrons at frequencies in the range 100 GHz to 150 GHz, for use in electron cyclotron heating applications. Early test vehicles have utilized a TE_{15,2,1} interaction cavity, and have achieved short-pulse power levels of 820 kW and average power levels of 80 kW at 140 GHz. Present tests are aimed at reaching 400 kW under CW operating conditions and up to 1 MW for short pulse durations. Work is also underway on modifications to the present design that will enable power levels of up to 1 MW CW to be achieved.

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 360 GHz(2).

To address this need, Varian has begun the development of 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-cloacetic class of waveguide mode(3,4), the current work utilizes TE_{mn} whispering-gallery modes where $m > n$. In contrast to circular-cloacetic 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(2), and in the Soviet Union(6).

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 power levels up to 400 kW at a frequency of 140 GHz. Testing of these tubes serves to validate the basic design of the electron gun and interaction circuit. In addition, operation at CW powers up to 400 kW provides useful information concerning whispering-gallery-mode operation at high average power levels.

Thus far, the first experimental tube has undergone 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. The second experimental tube has been constructed and 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.

Future test vehicles are now being designed to achieve full 1 MW CW operation. To be consistent with planned ECR heating experiments, 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 first two experimental gyrotrons, review the results of the four test iterations on the first tube, outline the test sequence for the second experimental tube, and discuss the major design issues involved in reaching the 1 MW CW goal in subsequent experimental gyrotrons.

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DESIGN OF FIRST TWO EXPERIMENTAL 1 MW GYROTRONS

The design of the first two experimental 140 GHz, 1 MW gyrotrons 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} 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 3% 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.

Further details of the design of the experimental 140 GHz, 1 MW gyrotrons have been published elsewhere(7).

TEST RESULTS ON FIRST EXPERIMENTAL TUBE

First Test

Tests on the first experimental 140 GHz gyrotron, with a whispering-gallery-mode interaction circuit, were performed between November 1987 and February 1988. During these initial tests, peak output powers up to 300 kW at 18 % efficiency were produced with pulse durations of less than 1 ms. Operation at longer pulse durations or higher peak powers was prevented by spurious oscillations in the beam tunnel between the electron gun and the interaction cavity. At high-peak-power or long-pulse operation, the spurious oscillations activated protective circuitry and turned off the gyrotron.

Following tests on the tube, the tube was disassembled and examined for possible damage. All portions of the tube were undamaged with the exception of the beam tunnel. A portion of the beam tunnel adjacent to the cavity was significantly damaged. The damage pattern was consistent with the presence of spurious oscillations in that region.

Second Test

For the second set of tests, an entirely new beam tunnel was employed. Geometry changes were made to

minimize the amount of stored energy present in the critical region of the beam tunnel near the cavity to prevent oscillations in that region. In addition, the cooling design for the beam tunnel was improved. All other major elements of the tube remained the same as in the first experimental iteration. The second series of tests were performed between June 1988 and October 1988.

During the second set of tests, an output power of 655 kW was obtained at 26 % efficiency at the nominal beam voltage of 80 kV during short-pulse operation. Further short-pulse tests resulted in output powers of 750 kW and 820 kW at beam voltages of 90 kV and 95 kV, respectively. Corresponding output efficiencies were 22 % and 21 %. The lower efficiencies were due to the value of Q chosen for the cavity. For optimum results at the higher voltage, higher Q cavities are required.

Following the short-pulse testing of the tube, long-pulse tests were carried out. At 10 ms pulse durations, output powers of 400 kW at 30 % efficiency were measured. However, as the pulse duration was stretched to 200 ms, degradations in the tube operation were observed, resulting in lower output power levels and efficiencies. Following about 10,000 pulses of greater than 10 ms in duration, significant levels of gas were observed in the tube and testing was stopped. An examination of the tube revealed cyclic fatigue damage to the cavity.

Third Test

To try to alleviate the cyclic fatigue problems observed in the cavity following the second series of tests, a new cavity design was conceived to lower ohmic losses in the cavity. The cavity Q was lowered to 350 from 500, resulting in a 20 % reduction in the power density on the cavity walls. No change was made to the mechanical design of the cavity. All other major elements of the tube were undamaged and remained in the tube for the third series of tests.

The third series of tests were carried out from November 1988 through December 1988. Initial short-pulse testing of the tube resulted in output power levels of 450 kW at 33 % efficiency. This data point is compared with large-signal theoretical predictions, using both cold-cavity and self-consistent analysis techniques, in Figure 1. A mode-map, showing output power levels for various values of main magnet current (cavity magnetic field) and gun-anode voltage, for a constant beam current of 17 A, is shown in Figure 2.

Rather than continue short-pulse tests at higher beam currents to reach higher output powers, long-pulse tests were carried out at the 400 kW level to determine if the cyclic fatigue problems encountered in the previous tests had been alleviated. During the long-pulse tests, no deleterious effects were observed up to 60 ms pulses where output powers of 400 kW at 31 % efficiency were obtained. However, at pulse durations of 80 ms, significant gassing and diminished performance were observed, leading to the cessation of tests. An examination of the tube again revealed cyclic fatigue damage to the cavity.

Figure 1. Experimental and theoretical efficiencies versus output power during third test of experimental 140 GHz gyrotron.

Figure 2. Output power mode map during third test of experimental 140 GHz gyrotron.

Fourth Test

For the fourth set of tests, a new mechanical design of the cavity was devised to minimize the effects of cyclic fatigue. An alternate electron gun design was also incorporated into the tube. The electron gun design produced a thinner electron beam at the expense of higher cathode loading. In addition, the beam optics were somewhat different than in the original design used in the three previous tests. The fourth set of tests were performed between March 1989 and June 1989.

Initial short-pulse parameter variation studies on the fourth test vehicle yielded some minor changes in tube performance. At an output power of 429 kW, the maximum obtainable efficiency was 29 %. Similar tests on the third test vehicle had yielded efficiencies up to 33 % with the same cavity design. The slight degradation in efficiency was attributed to the new electron gun design. There was evidence that beam performance degraded much more rapidly with

increasing current than observed with the tests employing the original electron gun design. In addition, it proved to be significantly more difficult to spread the beam evenly along the length of the collector than in earlier tubes. This effect was probably due in part to the thinner beam produced by the new gun design.

As in the previous set of tests, short-pulse parameter variation studies were only carried out for beam currents less than 20 A, prior to testing the average power capabilities of the cavity. However, rather than lengthening the pulse duration to approach CW operation, the duty cycle was increased instead. At an output power of 336 kW at 30 % efficiency, the duty factor was extended to 24 % (2 ms pulse duration, 120 pulses per second) for an average output power of 81 kW. No evidence of excessive gas pressure or power losses in the various monitored circuits was observed under these conditions, so the beam current was reduced and CW operation was attempted. After several tries at maintaining CW operation without excessive gassing, a sudden degradation in tube performance was observed, though the tube still retained its vacuum integrity. A visual inspection through the output window of the tube revealed a small area in the collector where melting had occurred. Following the observation of the collector damage in the fourth test vehicle, all of tests on the tube were halted.

STATUS OF SECOND EXPERIMENTAL TUBE

The second experimental 140 GHz, 1 MW pulsed, 400 kW CW gyrotron incorporates several new features aimed at alleviating various problems experienced during the tests of the first experimental tube. The new tube will retain the cavity design of the previous tube (lower value of loaded Q and mechanical design capable of withstanding cyclic fatigue environment) and incorporate an electron gun of the original design. Refinements to the beam tunnel have been included in the new tube design to further stabilize this region against spurious oscillations and several modifications to the collector have been made to detect and prevent the type of damage sustained in the last set of tests.

Assembly of the second experimental tube has been completed and initial short-pulse parameter variation studies on the tube are currently in progress. Following the short-pulse tests, the tube will be aged to long-pulse and ultimately CW operation with the goal of reaching 400 kW CW.

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.

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.

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. The first 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(6), with the incorporation of a quasi-optical coupler. This type of coupler transforms the circularly-polarized, whispering-gallery output mode into a linearly-polarized, Gaussian beam.

The principal drawback to this configuration is the relatively low efficiency of this approach in performing the desired conversion. At the present time major efforts are underway to try to improve the efficiency, either by shaping the launching structure or by carefully designing the mirror configuration. Both techniques are aimed at reducing the side-lobe losses inherent in the most basic version of the concept.

The second 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.

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.

CONCLUSIONS

The results obtained during the series of tests performed on the first experimental 140 GHz, 1 MW gyrotron represent an important step in reaching the 1 MW CW goal of the current development program. Further advances are expected in the tests on the second experimental tube that are currently in progress. Design work is well underway in preparation for the fabrication of experimental gyrotrons with the goal of achieving 1 MW CW operation at a frequency of 110 GHz.

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