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Gyrotron Oscillators for Fusion Heating

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ABSTRACT

Recent experiments have been performed to determine the ultimate power capability of a 28 GHz 200 kW CW gyrotron design. A power output of 342 kW CW was measured in these tests with an efficiency of 37%. Progress in the development of 60 GHz 200 kW pulsed and CW gyrotrons is discussed. An output of 200 kW with 100 msec pulse length has been achieved with the pulsed design.

INTRODUCTION

Gyrotrons to produce 200 kW pulsed or CW output at 28 GHz have been developed at Varian over the past several years. Similar devices for 60 GHz operation are currently in development*.

The 28 GHz gyrotrons have been described in detail in a previous publication[1]. The designs will be briefly summarized here, and some recent experience with them will be described.

The 60 GHz gyrotrons under development are similar in design concept to the 28 GHz devices. The major difference is the use of a superconducting magnet for the higher field required at 60 GHz. Other differences occur in the detailed design of the electron gun and the output window.

28 GHz GYROTRONS

Design values for the 28 GHz gyrotrons are summarized in the following table:

Power Output	200 kW
Magnetic Field	11 kG
Beam Voltage	80 kV
Beam Current	8 A
Efficiency	31 %
Velocity Ratio $v_\perp/v_\parallel$	2:1
Cavity Mode	TE_{021}
Output Guide Diameter	2.5 inch

A simplified cross section of the CW oscillator is shown in Figure 1. The output waveguide tapers up to a 5-inch diameter for the region where the beam is collected and then tapers back down to 2.5-inch diameter for the output. The pulsed oscillator has a 2.5-inch diameter collector and output guide.

The output window for the CW tubes is made of two closely spaced discs of ceramic with fluorocarbon coolant circulated in the space between the discs. This arrangement allows face cooling of the discs which is much more effective than edge cooling. The pulsed tubes use a single disc ceramic.

* Both development programs have been sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract W-7405-eng-26 with the Union Carbide Corporation.

Ten of the pulsed 28 GHz 200 kW gyrotrons have been constructed and are being used in various plasma experiments. Operation of these gyrotrons has been generally satisfactory. The control of beam current by cathode temperature has not been a problem area. The most troublesome aspect of the design so far has been the fragile nature of the output window. A recent design change has been made to make the window mechanically stronger. The experience with the revised design is limited, but good so far.

An investigation was made to determine if the pulsed design could be operated CW at reduced power level. Calculations indicated that burnout of the collector should occur with a beam power of 100 kW. Experiments were performed with a beam power of 32 kW. Satisfactory operation was obtained with a beam of 40 kV, 0.8 A CW. Under these conditions a power output of 10.5 kW was achieved with an efficiency of 33%. These results demonstrate the ability of the gyrotron to maintain high efficiency over a wide range of output power.

Experiments were performed to determine the ultimate power output capability of the CW design. It was found that optimum results were obtained if beam voltage was allowed to increase somewhat as beam current was raised beyond the design value. Figure 2 shows the measured variations of power output and efficiency as functions of beam current. For these results the beam voltage was also increased from 80 kV with the lower values of beam current up to 84 kV for the highest values.

The maximum power output achieved was 342 kW CW. The tube was operated at that level for about 10 minutes at which time a failure occurred in the outer window disc. An investigation indicated evidence of arcing on the outer surface of the window. It is not clear whether this was the cause or the result of the failure. In this type of failure, the vacuum of the tube is not affected. The tube was made operable again by a simple mechanical replacement of a new outer window. Total time of operation of the tube over the 300 kW level in these tests was about two hours.

60 GHz GYROTRONS

Design values for the 60 GHz gyrotrons are as follows:

Power Output	200 kW
Magnetic Field	24 kG
Beam Voltage	80 kV
Beam Current	8 A
Efficiency	31 %
Velocity Ratio $v_\perp/v_\parallel$	2:1
Cavity Mode	TE_{021}
Output Waveguide Diameter	2.5 inch

The required dc magnetic field is obtained using a superconducting solenoid magnet wound with niobium-titanium in a copper matrix wire. The magnet consists of a split pair for the main field, a gun bucking coil for beam formation, transverse steering coils and a room temperature collector bucking coil for controlling collector dissipation in a reasonable-length collector.

The superconducting magnet used in the tests so far was made by Magnet Corporation of America. It is designed for use with the coil leads permanently connected to external power supplies for maximum ease of adjustment. The built-in dewar capacities are 57 ℓ of helium and 21 ℓ of nitrogen. Average usage of coolants including transfer losses are about 1.1 ℓ/hour of helium and 0.5 ℓ/hour of nitrogen.

For the electron beam, formed by a magnetron injection gun, a ratio of transverse to axial velocity of two to one was chosen. A digital computer code was used to determine appropriate electrode shapes in the gun to generate the beam in a physically realizable magnetic field. The simulation predicted a spread in transverse velocity of ± 1.3%. Computer simulation was also used to minimize gun electrode electric field gradients.

For the pulsed tube, the output waveguide tapers from the cavity diameter up to a diameter of 2.5 inches, where the beam is collected. Because there is appreciable fringing of the magnetic field in the superconducting magnet, the 60 GHz pulsed tube tends to be much longer than the 28 GHz counterpart. The overall length is about 80 inches. One advantage of the longer collector is increased pulse length capability to 100 msec.

The output window for the pulsed oscillator is a single three-halves wavelength thick beryllia disc. A picture of the pulsed gyrotron installed in the superconducting magnet is shown in Figure 3.

Calculated output power and efficiency for the initial 60 GHz design are shown in Figure 4. The calculations assume a sinusoidal variation of microwave field with distance in the cavity. An inflection point is observed in the curves near a beam current of 12 A. This point appears to be associated with over-bunching of the electrons as they pass through the cavity. At the point of inflection the fields in the cavity are large enough to cause the bunch to form early in the cavity with debunching occurring toward the end of the cavity. At higher currents the induced cavity fields are higher and the bunching occurs twice within the cavity length with a resulting increase in efficiency.

Figure 5 shows a measured power versus beam current curve for the pulsed oscillator. The measured curve shows a similar inflection point but at a lower beam current than expected. This may be caused by the fact that the true cavity fields are somewhat gaussian in shape rather than sinusoidal.

The best results obtained with the 60 GHz pulsed oscillator are as follows:

Peak Output	200 kW ± 10%
Pulse Length	100 msec
Efficiency	34 %
Beam Voltage	80 kV
Beam Current	7.3 A
Frequency	59.6 GHz

A CW 60 GHz gyrotron is presently being tested. It is similar to the pulsed tube except that the output waveguide tapers up to 5 inches in diameter for the collector region and back down to 2.5 inches for the output window. The output window is a double-disc system using alumina ceramics and FC-75 coolant. Pulsed testing of the CW tube has been limited to peak power output of 170 kW because of interfering modes of oscillation near the desired mode in frequency. CW power output of 70 kW was measured in early testing.

CONCLUSIONS

Very useful 28 GHz gyrotron oscillator designs have been developed which produce 200 kW pulsed and CW output at 28 GHz. The maximum power produced at 28 GHz was 342 kW CW with efficiency of 37%.

Gyrotrons for pulsed and CW operation at 60 GHz are in the early stages of development. Pulsed output of 200 kW for 100 msec has been produced. CW output of 70 kW at 60 GHz has been achieved.

FIGURE 1

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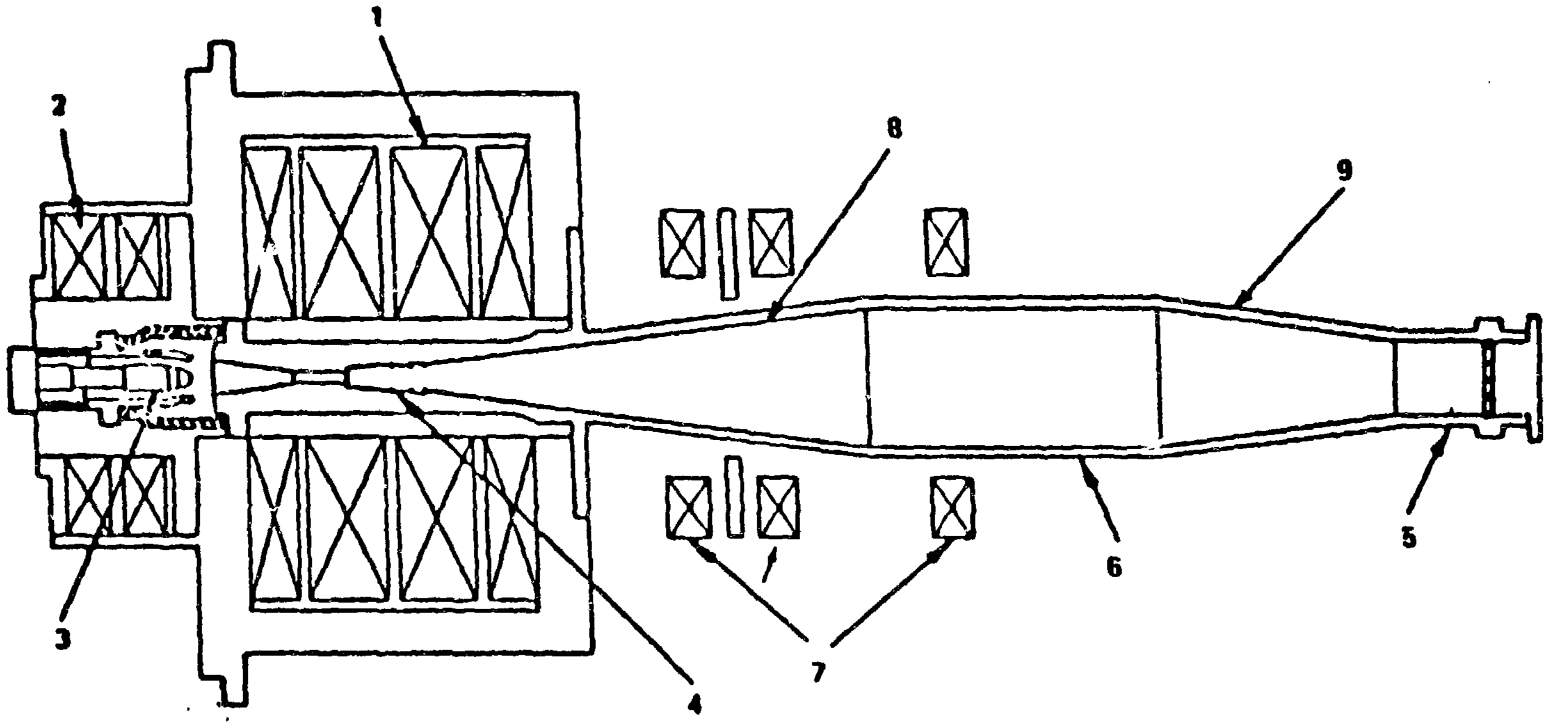
LAYOUT DRAWING OF A CW GYROTRON WITH TAPERED OUTPUT GUIDE



1. MAIN MAGNET COILS
2. GUN MAGNET COIL
3. ELECTRON GUN
4. CAVITY
5. OUTPUT WAVEGUIDE AND WINDOW
6. BEAM COLLECTOR AREA
7. COLLECTOR MAGNET COILS
8. OUTPUT GUIDE UP-TAPER
9. OUTPUT GUIDE DOWN-TAPER

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FIGURE 2

POWER AND EFFICIENCY VS BEAM CURRENT (VGA-8000 S/N 11) CW

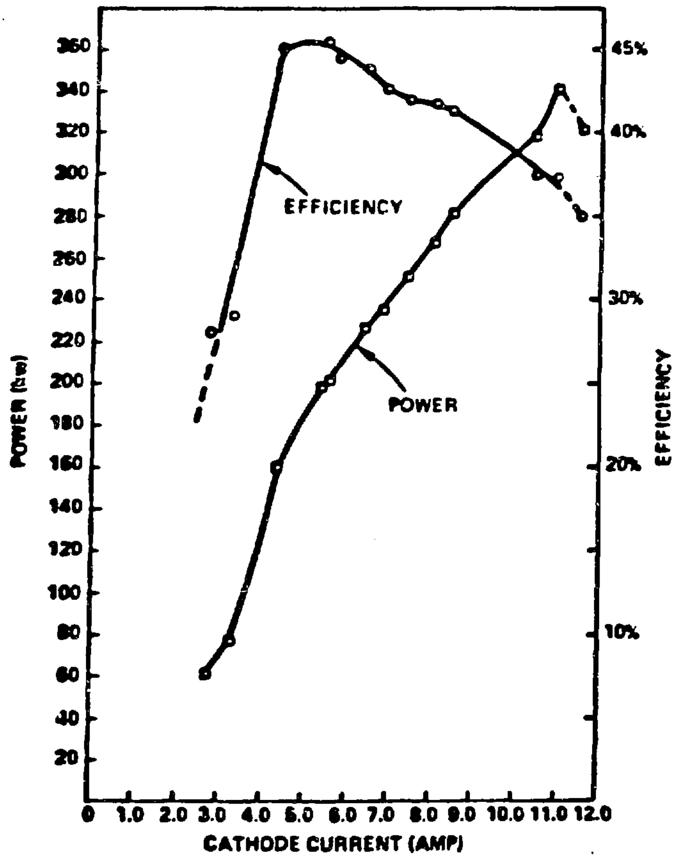

FIGURE 3

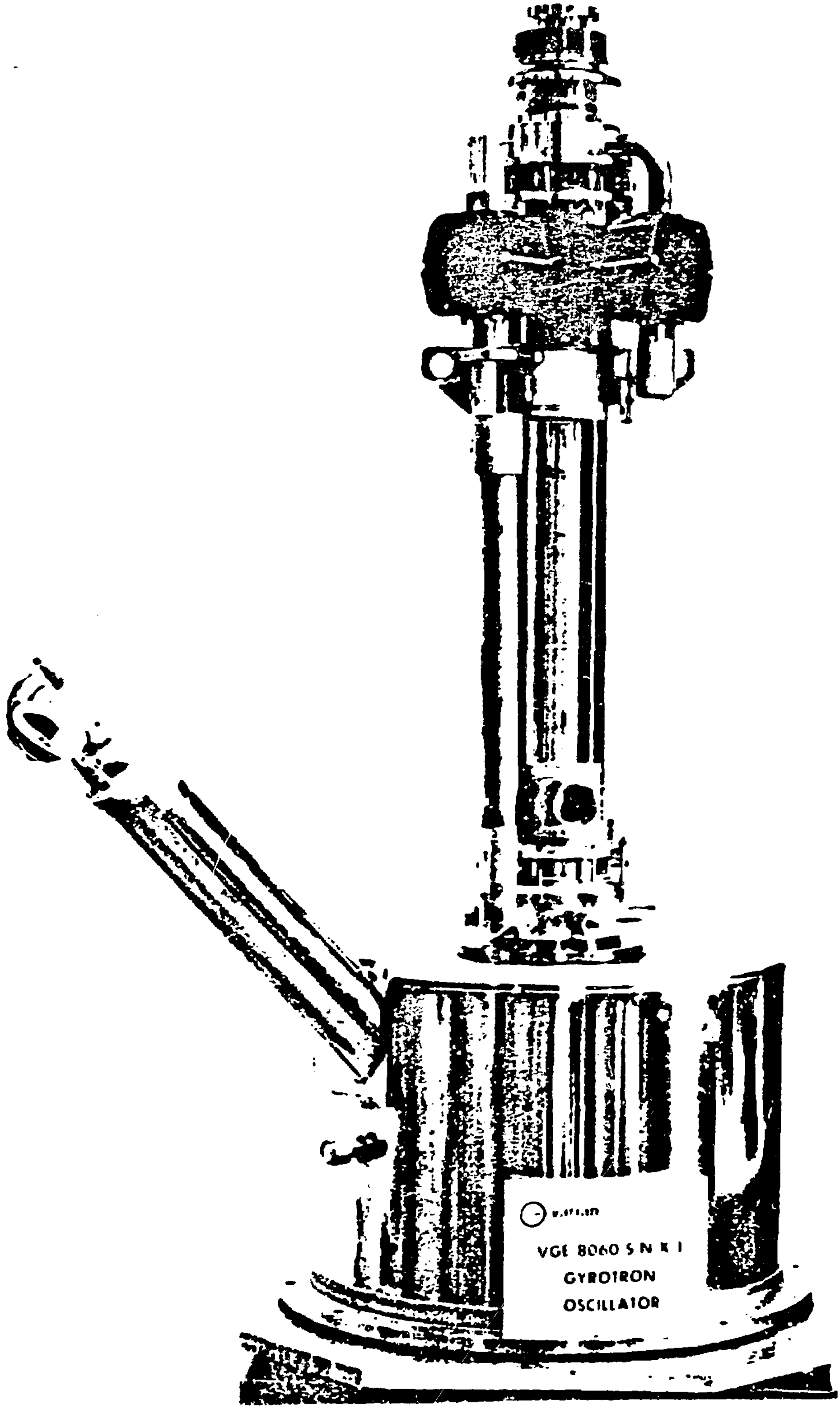

FIGURE 4

OUTPUT POWER AND EFFICIENCY VS BEAM CURRENT

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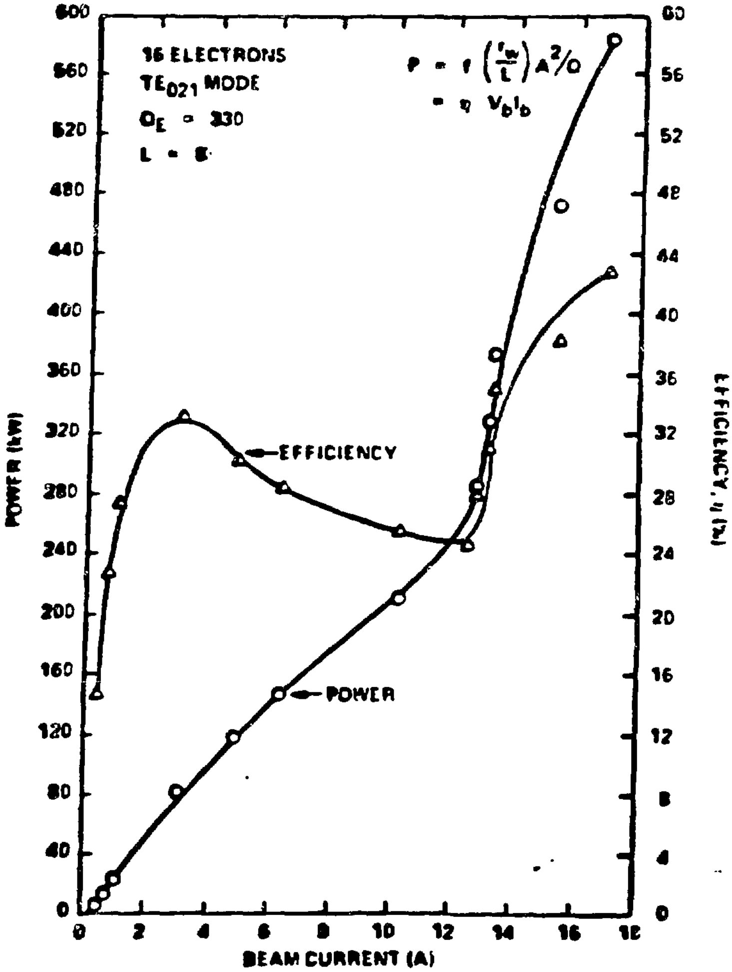

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FIGURE 5

MEASURED OUTPUT POWER VS BEAM CURRENT