A 60 GHz, 200 kW CW GYROTRON
WITH HIGH OUTPUT MODE PURITY*

CONF-841234--4

DE85 005283

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ABSTRACT

For the first time, a Varian 60 GHz gyrotron,
designed specifically to generate microwaves in a
single output mode, has been operated at power
levels up to 200 kW CW. High output mode purity is
required for the efficient utilization of gyrotrons
as high power microwave sources for electron
cyclotron resonance heating (ECRH) in magnetic
fusion plasmas. Using mode-specific directional
couplers, measurements of the output mode content
indicated that greater than 95% of the microwave
output was in the desired TE_{02} mode, with only
small percentages in the neighboring TE_{01} and TE_{03}
circular electric modes.

The pure mode CW design uses a 2.5-inch
diameter collector. The collector has a magnetic
field arrangment which capably avoids excessive
heating by distributing the 640 kW CW beam over a
sufficient collector area. With pure mode
operation, window temperatures are $10^{\circ}C$ to $15^{\circ}C$
higher than with mixed mode operation.

INTRODUCTION

The Varian 60 GHz, 200 kW CW gyrotron is being
developed for use in electron cyclotron resonance
heating (ECRH) in magnetic confinement fusion
devices. Several 200 kW, 100 msec pulse versions
of the 60 GHz tube, as well as similar tubes at
53.2 GHz, have already been employed in various
fusion experiments. Also, a number of high output
mode purity gyrotrons, similar to the CW design
described in Section 4, have been operated at pulse
lengths of 500 msec with 200 kW output at 60 GHz.
However, for fusion reactors where steady state or
quasi-steady state operation is necessary,
gyrotrons with CW capabilities are required.
Varian has developed 200 kW CW gyrotrons at 28 GHz,
and in addition to the 60 GHz CW Tubes currently
being tested (1), tubes at 35 GHz, 70 GHz, and
140 GHz are being designed for high power CW
operation.

*The 60 GHz gyrotron oscillator is being developed
under contract with Oak Ridge National Laboratory,
operated by Martin Marietta Energy Systems, Inc.,
for the U.S. Department of Energy, Office of Fusion
Energy, under prime contract DE-AC05-840R21400.

An additional requirement for many ECRH
experiments is the necessity to inject the
microwave power in a specific mode with a given
polarization and direction. This need implies that
the output mode of the gyrotron must be pure so
that efficient conversion into the proper injection
mode can be carried out. For the present 60 GHz
gyrotron in which the electron beam collector also
serves as the output waveguide for the microwaves,
the mode purity requirement places severe
restraints on the size and geometry of the
collector. The collector must be capable of
dissipating the entire CW beam power, up to 640 kW
in the present tubes, while at the same time, it
must transmit the rf to the output of the tube
without disturbing the purity of the mode.

To achieve a collector design which satisfies
both criteria, care must be taken in designing all
tapers and isolation gaps. This process becomes
more difficult at higher frequencies, since
collectors with similar cooling capabilities are
required for a given power level. This implies
that the physical size of a high frequency
collector must be about the same as that of one
employed at lower frequencies. However, at higher
frequencies, the coupling of the principal output
mode (TE_{02} for the 60 GHz gyrotron) to neighboring
modes (possessing similar wave numbers) becomes
stronger for a given waveguide diameter. This
means that the problem of mode conversion becomes
more difficult at higher frequencies.

MODE PURITY AND COLLECTOR POWER DISSIPATION

The original 60 GHz design incorporated a
5-inch diameter collector, shown in Figure 1. The
choice of 5 inches for the collector diameter was
made primarily to ensure that the collector could
withstand the power deposited by the impinging
electron beam. Another consideration was to
minimize the magnetic focusing required to spread
the beam evenly along the length of the collector.
However, mode conversion in this design was quite
severe.

To alleviate the mode conversion due to the up
and down tapers in the CW collector (see Figure 1),
the collector diameter was reduced to 2.5 inches,
the same as the 100 msec pulse gyrotron. This
eliminated the need for a downtaper and reduced the
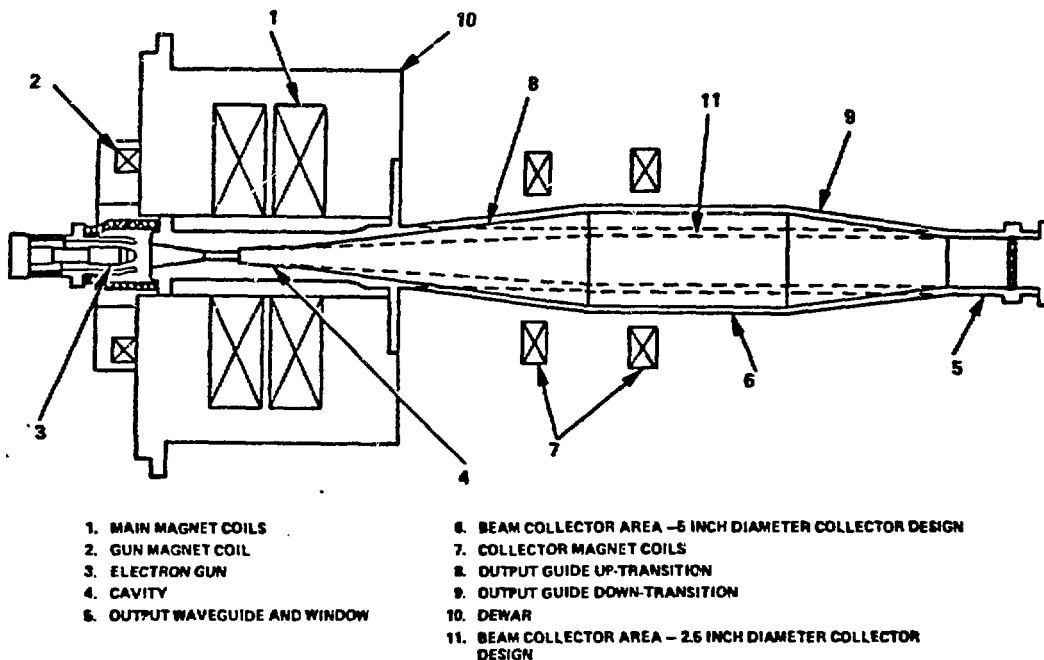amount of uptaper required before the collector.

Figure 1. Schematic of the 60 GHz Gyrotron. Present designs employing 2.5-inch diameter collectors are represented by the dashed lines, and earlier designs with 5-inch diameter collectors are shown by the solid lines.

1. MAIN MAGNET COILS
2. GUN MAGNET COIL
3. ELECTRON GUN
4. CAVITY
5. OUTPUT WAVEGUIDE AND WINDOW
6. BEAM COLLECTOR AREA —5 INCH DIAMETER COLLECTOR DESIGN
7. COLLECTOR MAGNET COILS
8. OUTPUT GUIDE UP-TRANSITION
9. OUTPUT GUIDE DOWN-TRANSITION
10. DEWAR
11. BEAM COLLECTOR AREA — 2.5 INCH DIAMETER COLLECTOR DESIGN

However, the length of the collector remained the same as the original 5-inch version — approximately 24 inches longer than that of the pulse tube. Mode purity calculations of this collector configuration, based on the generalized telegrapher's equations and a finite element code, indicated excellent mode purity potential. This was verified by measurements using mode selective directional couplers provided by C. Moeller of GA Technologies (3,4,5) on pulsed tubes. Pulsed tests

on a CW tube, built with the 2.5 inch diameter collector, indicated that approximately 95.3% of the microwave output was in the TE_{02} mode, while 2.3% and 2.4% were measured in the TE_{01} and TE_{03} modes, respectively.

In order to safely dissipate the collected electron beam along the length of the collector, a computer analysis and thermal measurement technique was developed. The computer code followed the
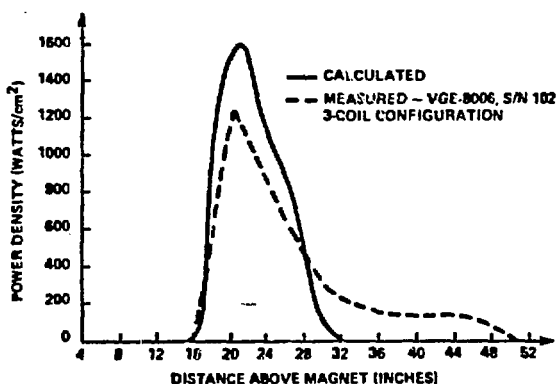

Figure 2. Collector power density along axis for three large coils, calculated vs measured on a VGE-8006-102.
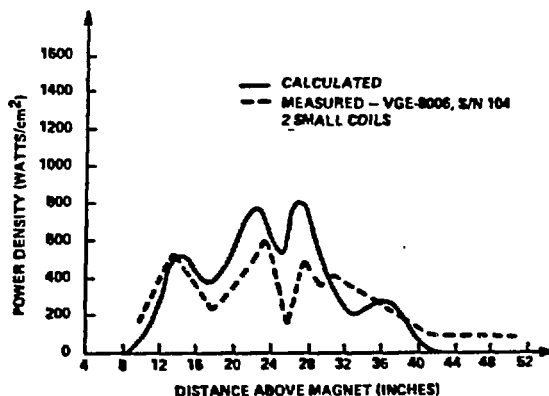

Figure 3. Collector power density along axis for two small coils, calculated vs measured on a VGE-8006-104. No Rf.

trajectories of many particles, assuming 1) an initially uniform density of guiding centers along the width of the beam, 2) circular symmetry, 3) radial space charge effects, 4) a random phase around the guiding center, and 5) zero beam temperature (although a beam temperature could be specified). A thermal measurement technique consisting of resistance temperature detectors (RTD) was used to measure the energy deposition of a single short pulse (typically 200 msec) on an uncooled collector. Calculations and measurements (without RF) are in very good agreement, as shown in Figures 2 and 3.

Two types of collector coils were used, an 18" ID solenoid and a wrap-on 4" ID solenoid. It was found that the large coils did not adequately spread the beam. They merely shifted the landing sites. The small wrap-on coils, however, provided a more localized control of the magnetic field profile, which enabled more control of the electron beam power density.

The collector magnetic field profile was optimized to handle the electron beam power dissipation in, both, the cases of no RF power and 200 kW RF power. The electron beam was safely dissipated by maintaining hot spot power densities below 1 kW/cm^2 along the collector.

FIRST 200 kW CW OPERATION WITH A PURE OUTPUT MODE

Following pulse tests on the tube (mode measurements and collector power densities), the tube was slowly brought up to power in CW operation. As on tests of the previous CW tube (2), the window temperature was carefully monitored using the IR imaging system (6). During these tests, it was noticed that the temperature distribution on the window closely resembled the power distribution of the TE_{02} mode, as opposed to the widely varying distribution observed on the previous CW tube with a mixed output mode. In Figure 4, we show a photograph of the IR image of the window. The bright circle corresponds in position to the first electric field maximum of the TE_{02} mode. The apparent asymmetry of the ring is due, in part, to the spatial variation in the transmission properties of the grided walls of the output waveguide through which the window is monitored. In addition, a small asymmetric mode content of about 1% may be present. A second ring does not appear in the photograph because the temperature is below the threshold of the imaging system.

In Figure 5, we show a plot of the maximum window temperature as a function of increasing microwave power. When the output power was raised to 207 kW CW, the maximum temperature on the window was 113°C. This temperature was 13°C higher than that observed on the previous CW tube with a mixed output mode operated at the same power level (2). This difference is probably due to the pure mode output of the present tube, though small changes in the window design might also be responsible for this difference. Since the coolant side of the window has a temperature 10°C to 20°C lower than

the air side, there was a 20°C to 30°C safety margin between the temperature of the cooling fluid and its boiling point.

(a) (b)

1. CENTER OF WINDOW
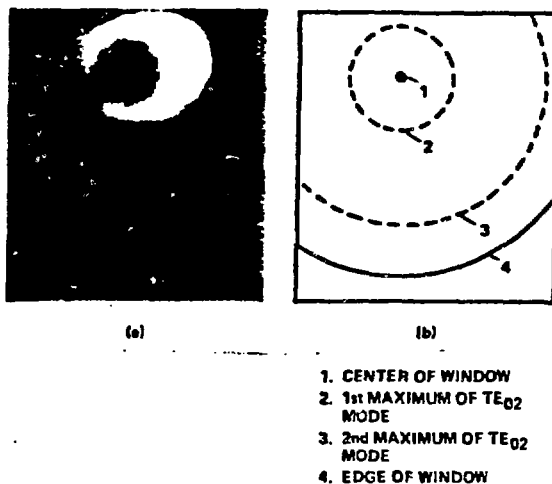2. 1st MAXIMUM OF TE_{02} MODE
3. 2nd MAXIMUM OF TE_{02} MODE
4. EDGE OF WINDOW

Figure 4. (a) IR image of output window during CW operation of 60 GHz Gyrotron with a pure output mode; (b) Predicted orientation of the TE_{02} electric field maxima on output window of 60 GHz Gyrotron.
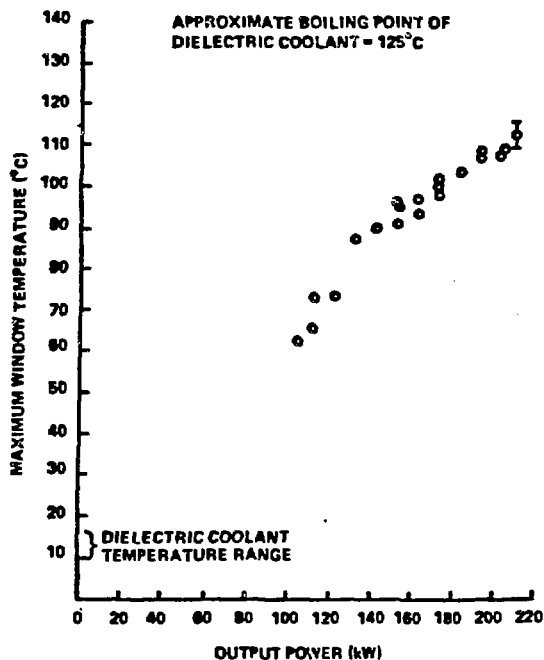

Figure 5. Maximum window temperature vs output power for the 60 GHz Gyrotron.

The parameters for the tube while operating at 207 kW CW were:

Output power = 207 kW
Frequency = 59.74 GHz
Beam voltage = 80.3 kV
Gun anode voltage = 16.6 kV
Beam current = 7.5 A
Cavity magnetic field = 22.64 kG
Magnetic taper across cavity = 4.0%
Cathode magnetic field = 1.23 kG
Output efficiency = 34.4%
Internal measured power losses = 14.5 kW
  (cavity, seals, window, etc.)
Interaction efficiency = 36.8%

Peak window temperature = 113°C
Duration of test at 207 kW CW = 40 min.

During the tests, no large variation in window temperature was noticed when different parameters were varied to change the output power, as opposed to the CW tube with the mixed output mode. The tube ran quite smoothly during the CW tests, indicating that the collector successfully dissipated the energy of the spent electron beam. During a second set of tests, the tube was operated at a power level of 200 kW CW for two hours with no interruptions or degradation in performance.

Further tests on the same tube were conducted to observe the ability of the tube to withstand thousands of thermal cycles while operating at 200 kW power levels.

A thermal cycle consists of a continuous "on" period for a minimum of three seconds and an "off" period of at least five seconds. For pulse lengths of over 0.5 seconds, the beam current of the temperature-limited magnetron injection gun (MIG) droops, due to emission cooling. By properly boosting the cathode heater power, a constant beam current was obtained. Over ten thousand thermal cycles were sustained before switching experiments to demonstrate 30 second pulse widths using the cathode heater booster. However, a vacuum side window failure occurred when the tube was operating at 150 kW output on a 30 second pulse. An investigation is underway to determine the cause of failure. Beam overvoltage and cyclic fatigue may have been contributing factors.

CONCLUSIONS

The operation of the Varian 60 GHz gyrotron at power levels of 200 kW CW with a pure output mode represents an important step in providing fusion experiments with the reliable high frequency microwave sources required to verify the ECRH concept in a reactor-relevant regime. Further tests on the present 60 GHz CW tube design will soon be carried out to observe the ability of the tube to withstand 35,000 thermal cycles while operating at 200 kW CW power levels. These tests will indicate the ultimate lifetimes of the tube under conditions appropriate for use in a fusion plasma test environment. Future gyrotron efforts at higher powers and/or higher frequencies are already planned or under way. These efforts will rely heavily on the technology developed in achieving the goals of the 60 GHz gyrotron development effort.

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