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FIRST 200 kW CW OPERATION OF A 60 GHz GYROTRON*

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ABSTRACT

The gyrotron is a microwave tube which employs the electron cyclotron maser interaction to produce high power output at millimeter wavelengths. It has important and growing applications for heating of plasmas in controlled thermonuclear fusion experiments. The Varian 60 GHz gyrotron has recently generated microwave power in excess of 200 kW during CW operation, with excellent dynamic range and operating stability. This is the highest average power ever produced by a microwave tube in the millimeter wave region. A description of the gyrotron design and test results are presented.

INTRODUCTION

The gyrotron is a device which extracts microwave power at millimeter wavelengths from an electron beam, using the electron cyclotron resonance condition. The theory of gyrotron operation has been summarized in the review of cyclotron resonance devices by Symons and Jory[1].

A brief compilation of results for CW power generated at millimeter wavelengths is given in Table 1.

Table 1
Peak CW Power Results

Power (kW)	Frequency (GHz)	Efficiency (%)	Reference
342	28	37	2
214	60	33	
22	150	22	3
1.5	325	6.2	4

This paper describes the Varian 60 GHz gyrotron that recently produced the 214 kW CW result noted above, and presents design parameters and test results.

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CW gyrotrons at or near 60 GHz have applications for plasma heating in controlled thermonuclear fusion experiments.

GYROTRON DESIGN

The design values for the 60 GHz gyrotron are as follows:

Frequency	60	GHz
Power Output	200	kW
Duty	to	CW
Magnetic Field	23.5	kG
Beam Voltage	80	kV
Beam Current	8	A
Nominal Efficiency	31	%

An outline drawing of the gyrotron is shown in Figure 1. A discussion of the major gyrotron components follows.

Electron Gun

The gyrotron employs a magnetron injection gun which produces an 80 kV, 0 – 8 A beam with a computed transverse velocity spread of $< \pm 3\%$. The gun is designed to yield a beam with a perpendicular-to-parallel velocity ratio (α) of 2.0. The gun cathode, made of impregnated tungsten, is temperature limited to control cathode current.

Interaction Circuit

In previous Varian 60 GHz tubes, the competing TE_{221} mode has limited the range over which the tube can be operated in the desired TE_{021} mode. The interaction circuit of this tube consists of a complex cavity specifically designed to eliminate competition from the TE_{221} mode over a broad operating region.

Figure 2 shows the magnetic field lines in a TE_{011}/TE_{021} complex cavity. The first section of the cavity is resonant at 60 GHz in the TE_{011} mode, and effectively pre-bunches the electrons without exciting competing modes. The pre-bunched beam then enters the main cavity, in which energy is extracted from the electron beam in the desired operating mode, TE_{021}. The closed-cavity idealization shown here is useful for preliminary analyses of cavity performance. The final cavity design accounts for the detailed effects of the output coupling from the taper. Exact cavity geometries are determined by finite element electro-magnetic computer codes.

Figure 3 shows the coupling of the cavity to the output taper for the actual 60 GHz gyrotron configuration. The design includes an iris at the cavity exit which controls the amount of power that diffracts out of the cavity. The loaded Q of the cavity is thus determined by the iris dimensions.

Magnet

Two superconducting magnet coils are located symmetrically around the complex cavity. The nominal magnetic fields is 23.5 kG.

The magnet system also includes a gun bucking coil for beam formation, transverse beam steering coils, and a room-temperature collector bucking coil to distribute the beam evenly along the inside surface of the collector. The collector and tapers also act as the output waveguide for the rf from the cavity exit to the output window.

Output Window

The output window assembly consists of two closely spaced alumina disks with a thin layer of an inert fluorocarbon coolant FC-75 (trademark of 3M Company) flowing between the disks. Thus, the ceramics are face cooled over a large surface area, providing much greater heat removal than from an edge-cooled, single-disk window. This design allows tube operation at high average power without window damage. The FC-75 was chilled to about 15°C in order to improve heat transfer and lower ceramic temperatures.

TEST RESULTS

Pulsed Testing

Pulsed data were taken at one to two percent duty rates, typically at pulse durations of 0.5 msec. As calculations indicated that the efficiency would vary with magnetic field taper for this design, data were taken for positive magnetic field tapers of 0 to 9% along the axial extent of the cavity. The nominal magnetic field is considered to be the field at the geometric center of the cavity.

Figure 4 shows clearly that by changing the gun anode voltage, the output power varies smoothly from 0 to 200 kw without mode competition or other instabilities. The 2.5 kv adjustable range of gun anode voltage gives much greater dynamic range than the 1 kv commonly seen in gyrotrons without complex cavities. The oscillation map (Figure 5) shows almost no competition from the TE_{22} mode. The region of maximum power (= 210 kw for a beam current of 8 a with a 2% positive magnetic taper) is in the center of TE_{021} parameter space, accounting for the excellent dynamic range of the tube. The 50 GHz mode does not degrade tube stability or performance. The source of the 50 GHz mode is not known, but it doesn't appear to be generated in the cavity.

At 3% positive magnetic taper, the peak efficiency increased to 35%, yielding a power of 230 kw at a beam current of 8 a. The excellent dynamic range and operating stability seen with a 2% magnetic taper were maintained.

At a 6% positive magnetic taper, an efficiency of 39% was recorded, yielding a power of 250 kw. At 9% taper, 250 kw power was again achieved at 39% efficiency. However, at 6 to 9% tapers, the dynamic range was markedly reduced compared to lesser tapers. The high magnetic tapers detrimentally affect beam formation and transmission in the gun and compression regions, causing gun-anode and body interception, thus reducing dynamic range.

With no magnetic taper, efficiencies dropped drastically, so that 200 kw was not achievable at 8 a of beam current, although the tube remained free of mode competition.

Figure 6 shows theoretical and experimental efficiencies for varying magnetic taper and beam currents. At 8 a beam current there is excellent agreement for all magnetic tapers. At 5 a there is good agreement for tapers of 6% or less. At 3 a the predicted efficiencies are ten to twenty points higher than measured. The discrepancies at low beam currents are possibly due to the effects of beam loading or window mismatch on the loaded Q of the cavity while the discrepancies at high magnetic tapers are due to the beam propagation problems mentioned earlier. In general, however, the agreement is good and confirms the validity of the computer techniques used to design the complex cavity.

In summary, pulse data show that the complex cavity operated at 2 to 6% magnetic tapers successfully eliminated mode competition over a broad parameter space at 200 kw power levels. This is a marked improvement in dynamic range and stability over previous standard cavity designs.

CW Results

All CW testing employed an IR imaging system to monitor the temperature of the airside of the output window. Window temperatures varied markedly with operating parameters, although tube power output remained constant. This is due to slight frequency shifts that alter the phase of the mode mixture at the window.

On June 8, 1983 the first 60 GHz 200 kW CW operation was achieved at the following conditions:

Frequency	59.82 GHz
Output Power	206 kW
Duty	100 % (CW)
Beam Voltage	80.3 kV
Beam Current	7.2 A
Efficiency	35.6 %
Peak Window Temp	100 °C

The tube ran for 25 minutes, was shut off by a crowbar, and then ran for another 35 minutes for a total of one hour at 206 kW CW. In subsequent testing, the tube ran at 214 kW CW for one hour without a crowbar. The peak window temperature was 101°C. An example of the variation of output power as a function of beam current is shown in Figure 7.

In summary, the achievement of 200 kW CW operation fulfills the major goal of the 60 GHz development program. The IR imaging system proved to be an invaluable aid in protecting the output window during high average power operation.

* The 60 GHz gyrotron oscillator is being developed under contract with Oak Ridge National Laboratory, operated by Union Carbide Corporation for the U.S. Department of Energy under prime contract W-7405-eng-26., Office of Fusion Energy.

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FIGURE 1. 60 GHz CW GYROTRON

FIGURE 2. TE_{011}/TE_{021} COMPLEX CAVITY

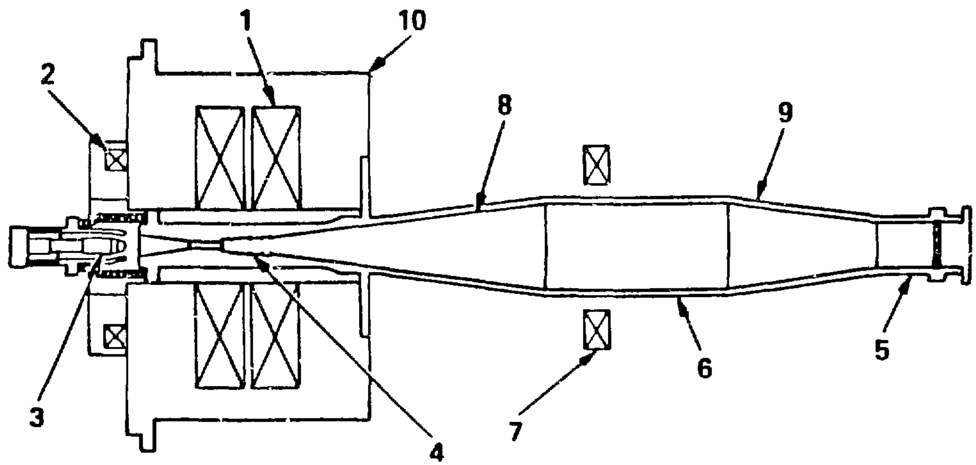
FIGURE 3. STEP CAVITY MODELED BY "OPEN CAVITY SUPERFISH"

FIGURE 4. OUTPUT POWER vs GUN ANODE VOLTAGE WITH A 2% MAGNETIC TAPER ACROSS THE CAVITY FOR THE VGE-8006, S/N X-6

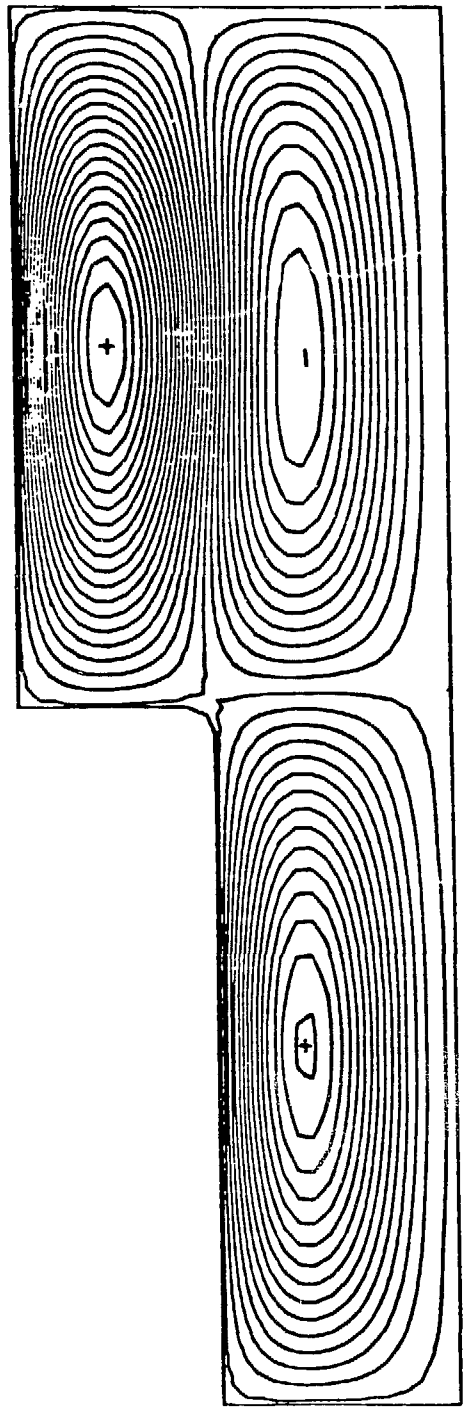
FIGURE 5. OSCILLATION MAP WITH A 2% MAGNETIC TAPER ACROSS THE CAVITY FOR THE VGE-8006, S/N X-6

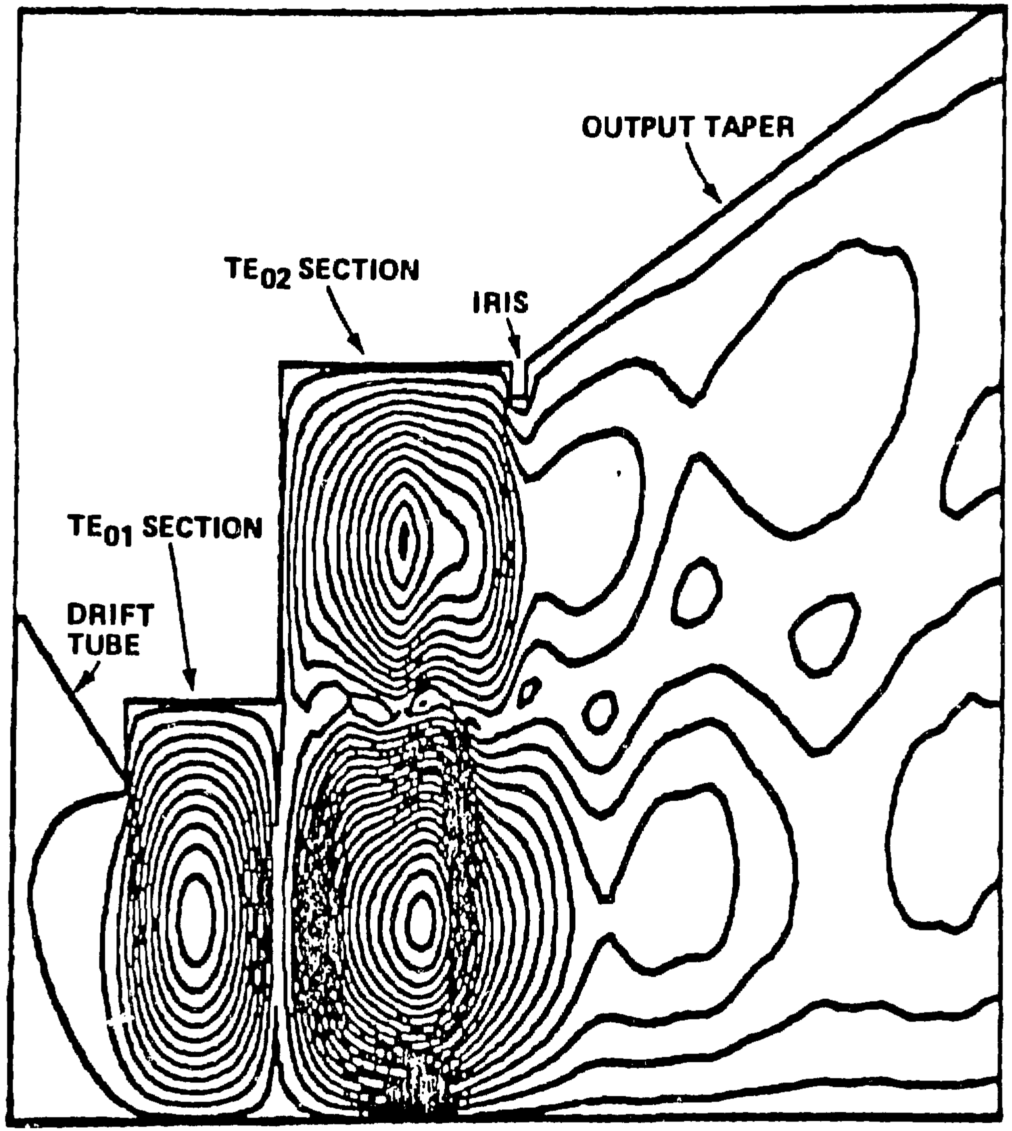
FIGURE 6. COMPARISON OF OPTIMUM EFFICIENCIES AS A FUNCTION OF MAGNETIC FIELD TAPER FOR DIFFERENT BEAM CURRENTS, AS PREDICTED BY THEORY AND OBSERVED ON VGE-8006, S/N X-6. EFFICIENCIES ARE OPTIMIZED WITH RESPECT TO THE AVERAGE MAGNETIC FIELD ACROSS THE CAVITY.

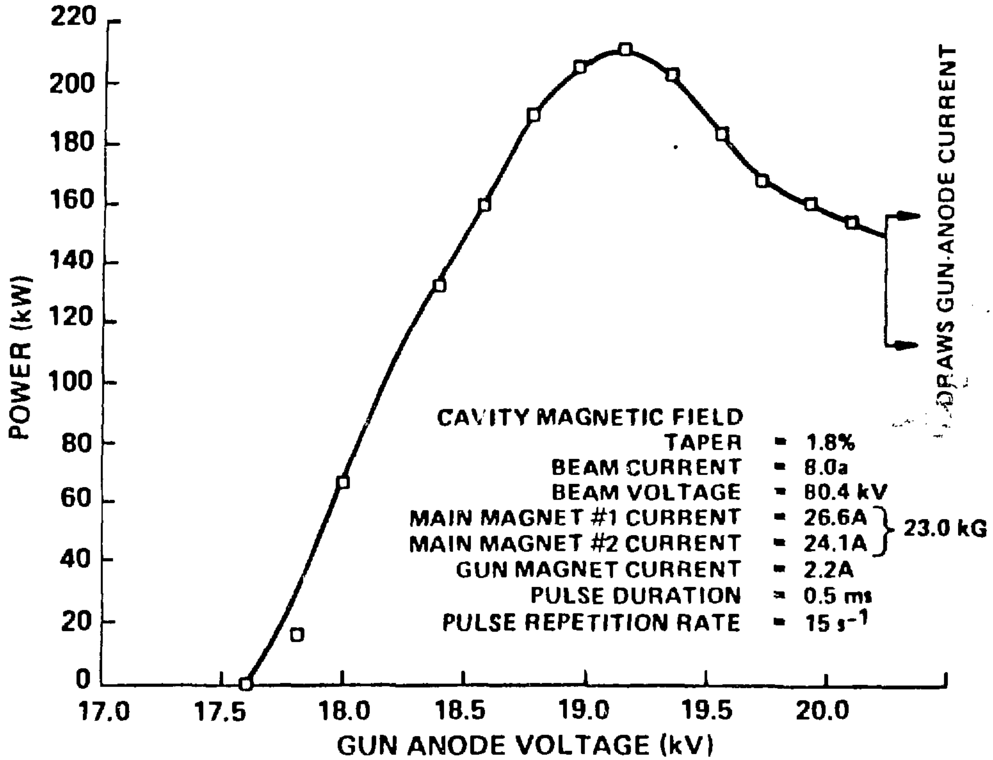
FIGURE 7. POWER vs BEAM CURRENT FOR X-6 – CW OPERATION



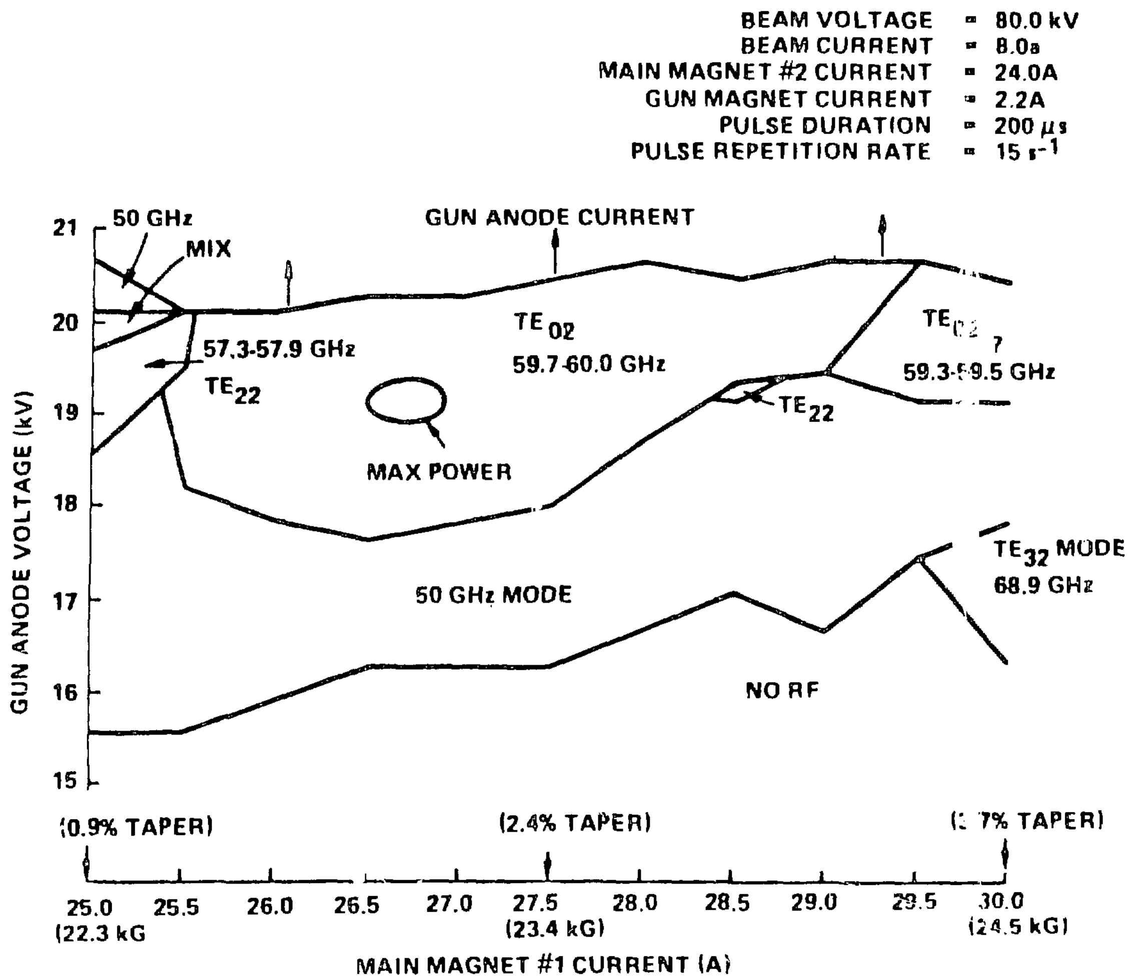
1. MAIN MAGNET COILS
2. GUN MAGNET COIL
3. ELECTRON GUN
4. CAVITY
5. OUTPUT WAVEGUIDE AND WINDOW
6. BEAM COLLECTOR AREA
7. COLLECTOR MAGNET COILS
8. OUTPUT TAPER
9. OUTPUT DOWN-TAPER
10. DEWAR



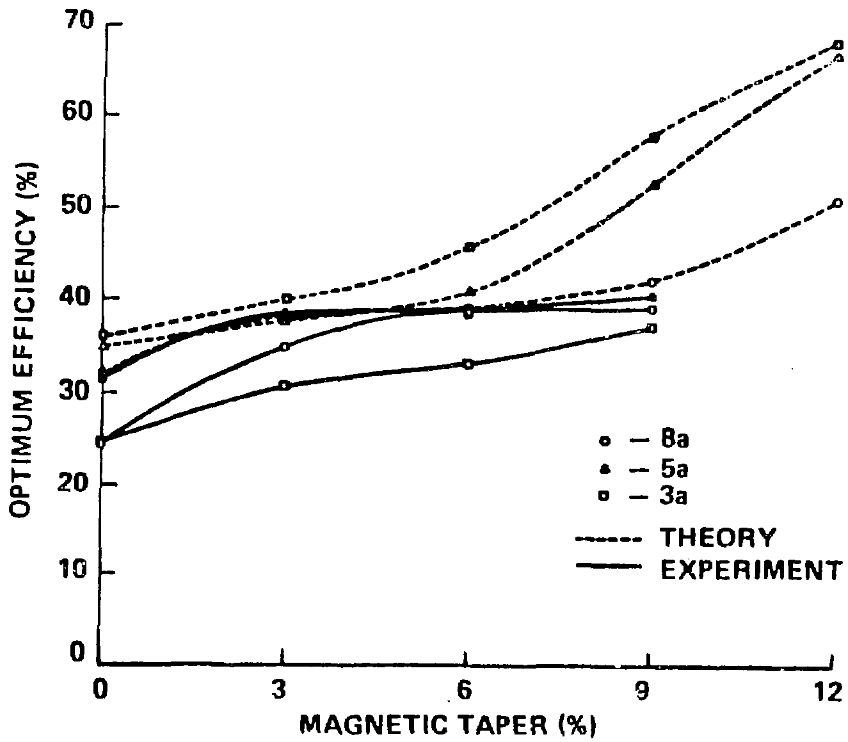

OUTPUT TAPER
TE02 SECTION
IRIS
TE01 SECTION
DRIFT
TUBE



220
200
180
160
140
120
100
80
60
40
20
0
POWER (kW)
17.0
17.5
18.0
18.5
19.0
19.5
20.0
GUN ANODE VOLTAGE (kV)
DRAWS GUN-ANODE CURRENT
CAVITY MAGNETIC FIELD
TAPER = 1.8%
BEAM CURRENT = 8.0a
BEAM VOLTAGE = 80.4 kV
MAIN MAGNET #1 CURRENT = 26.6A
MAIN MAGNET #2 CURRENT = 24.1A
23.0 kG
GUN MAGNET CURRENT = 2.2A
PULSE DURATION = 0.5 ms
PULSE REPETITION RATE = 15 s-1

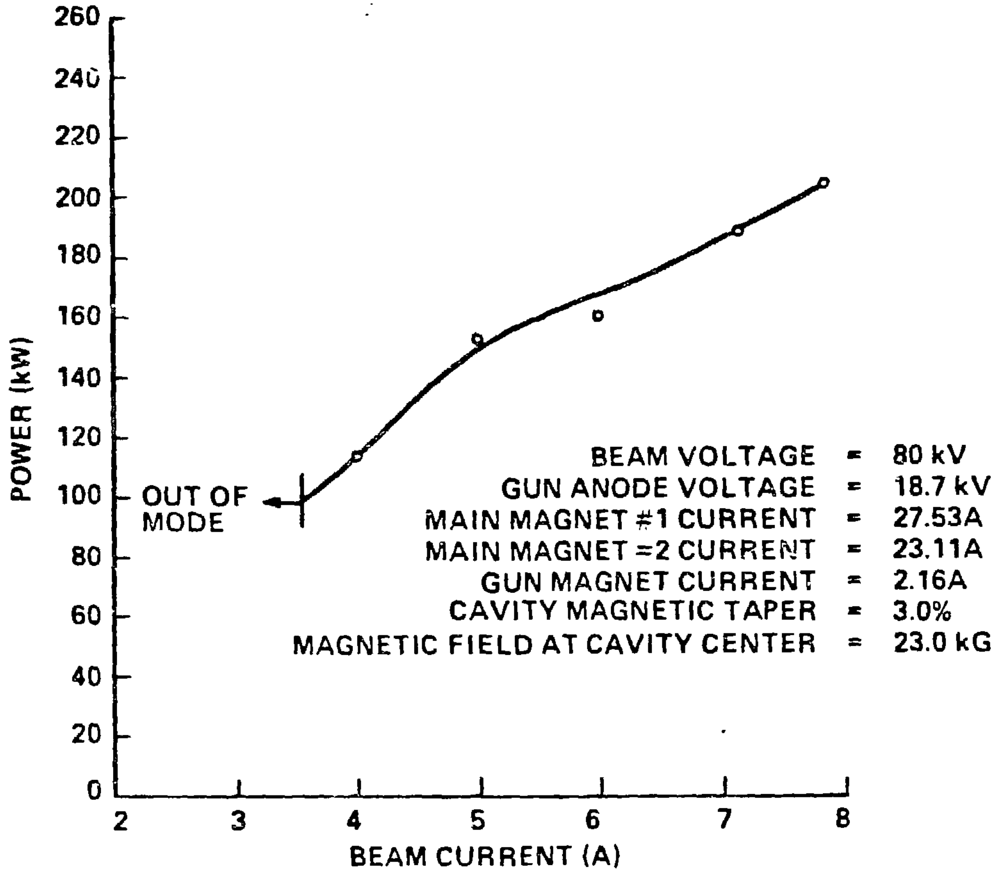


BEAM VOLTAGE = 80.0 kV
BEAM CURRENT = 8.0a
MAIN MAGNET #2 CURRENT = 24.0A
GUN MAGNET CURRENT = 2.2A
PULSE DURATION = 200 μs
PULSE REPETITION RATE = 15 s-1
50 GHz
MIX
GUN ANODE CURRENT
57.3-57.9 GHz
TE22
TE 02
59.7-60.0 GHz
MAX POWER
TE22
50 GHz MODE
TE32 MODE
68.9 GHz
NO RF
GUN ANODE VOLTAGE (kV)
21
20
19
18
17
16
15
(0.9% TAPER)
(2.4% TAPER)
25.0
(22.3 kG)
25.5
26.0
26.5
27.0
27.5
(23.4 kG)
28.0
28.5
29.0
29.5
30.0
(24.5 kG)
MAIN MAGNET #1 CURRENT (A)



70
60
50
40
30
20
10
0
OPTIMUM EFFICIENCY (%)
0
3
6
9
12
MAGNETIC TAPER (%)
— 8a
— 5a
— 3a
THEORY
EXPERIMENT

Figure 6



POWER (kW)
260
240
220
200
180
160
140
120
100
80
60
40
20
0
OUT OF MODE
BEAM VOLTAGE = 80 kV
GUN ANODE VOLTAGE = 18.7 kV
MAIN MAGNET #1 CURRENT = 27.53A
MAIN MAGNET #2 CURRENT = 23.11A
GUN MAGNET CURRENT = 2.16A
CAVITY MAGNETIC TAPER = 3.0%
MAGNETIC FIELD AT CAVITY CENTER = 23.0 kG
2
3
4
5
6
7
8
BEAM CURRENT (A)