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DEVELOPMENT PROGRAM FOR A 200 kW, CW, 28-GHz GYROKLYSTRON

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Quarterly Report No. 10

July through Sept. 1978

Prepared by
Varian Associates, Inc.
Palo Alto Microwave Tube Division
611 Hansen Way
Palo Alto, California 94303

for
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830

operated by
UNION CARBIDE CORPORATION

for the
DEPARTMENT OF ENERGY

Contract No. W-7405-eng-26

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ABSTRACT

The objective of this program is to develop a microwave amplifier or oscillator capable of producing 200 kW CW power output at 28 GHz. The use of the gyrotron or cyclotron resonance interaction is being pursued.

During this quarter, rebuilding of the second CW oscillator was accomplished. The tube was shipped to Oak Ridge, and considerable operation was realized at power levels up to 50 kW CW. This included operation heating a plasma load in EBT.

Construction of the third CW oscillator was completed. Design changes and test results are described. The design changes did not result in significantly improved performance.

Alternative output coupling schemes were studied with emphasis on axisymmetric coupling straight through 5" or 2.5" beam collectors. Computer simulation was used to analyze beam power distribution in the collector regions.

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I. INTRODUCTION

The objective of this program is to develop a microwave amplifier or oscillator capable of producing 200 kW of CW power at a frequency of 28 GHz. In addition, it is intended that the program will serve as the first step toward development of an amplifier to produce a similar power level at a frequency of 120 GHz. Feasibility for the 120-GHz device will be demonstrated whenever practical in the design of the 28-GHz amplifier. Tunability or bandwidth is not considered an important parameter in the design, but efficiency is. Mode purity in the output waveguide is not a requirement for the device, but the circular E mode is considered desirable because of its low loss properties.

With these objectives in mind, the decision was made to pursue an approach based on a cyclotron resonance interaction between an electron beam and microwave fields. The detailed arguments leading to this choice are contained in the final report of the preceding study program.[1] The device configuration of particular interest, called a Gyrotron, has been discussed in recent literature.[2] It employs a hollow electron beam interacting with cylindrical resonators of the TE_{0m1} class. The experimental Gyrotrons described in the literature have all been of the form of single-cavity oscillators. However, a similar device[3] has demonstrated moderate (16 dB) gain as an amplifier.

A goal of this development program is to achieve an amplifier having significantly higher gain (30 dB). Stability of the device becomes a very important technical consideration at this level of gain. To capitalize fully on the advantages of the cyclotron resonance interaction, large beam diameters are used. This exposes the device to the effect of microwave coupling between amplifier stages through the beam tunnel. Prevention of this coupling is an important consideration in the design.

The optimum beam for the cyclotron resonance interaction is one in which the electrons have most of their energy in velocities perpendicular to the axial magnetic field. Another requirement is that the small component of axial velocity be essentially the same for all electrons. An electron which has a different axial velocity will not interact efficiently. Generation of a beam with high transverse velocity and small axial velocity spread is another important design problem.

The approach chosen to generate the beam is a magnetron type of gun as was used in the devices described in the Russian literature. With this type of gun, the shaping of the magnetic field in the gun region becomes quite important.

As a result of the excellent performance of the pulsed oscillator producing up to 248 kw of peak power at 28 GHz with good efficiency[4], the emphasis of the program has been shifted to stress the construction and delivery of CW oscillators.

During this quarter, rebuilding of the second CW oscillator was accomplished. The tube was shipped to Oak Ridge and considerable operation was realized at power levels up to 50 kW CW. This included operation heating a plasma load in EBT.

Construction of the third CW oscillator was completed. This tube had a number of design changes which were intended to improve performance, particularly with respect to loading undesired resonances to minimize mode conversion of the output power. Test results with this tube are described.

Design work was continued on alternative output coupling techniques. Approaches considered include spherical mirrors, a 2.5" diameter straight through output guide and beam collector, a taper to 5" diameter collector with 5" window, and a taper to 5" with a taper back down to a 2.5" window.

II. CW OSCILLATOR NO. 2

A. THIRD REBUILD

This tube was intended for operation at Oak Ridge at the 50 kW CW power level. Near the end of the previous quarter, it demonstrated 45 kW CW at Oak Ridge, but subsequently lost vacuum. The tube was returned to Varian for analysis. It was determined that a leak had developed between the cathode stem oil channel and the vacuum.

B. FOURTH REBUILD

The tube was rebuilt using a different gun. A collector braze joint opened up during bake out.

C. FIFTH REBUILD

The collector joint was rebrazed. The tube was tested to 82.7 kw peak output power on a pulsed basis. The tube was then aged to 37.1 kW, CW at Varian before being requested by Oak Ridge. The operating parameters for the pulsed and CW operation are shown in Table 1. Spurious oscillations were observed under some magnetic field settings from 26.675 GHz to 26.801 GHz, from 26.930 GHz to 26.932 GHz and from 27.010 GHz to 27.134 GHz.

In July, the tube was shipped to Oak Ridge where final aging was completed up to 50 kW CW. During August and September, the tube was operated at power levels in the range of 30 to 50 kW CW including operating with plasma heating in EBT.

TABLE 1

Operating Parameters at Varian for the Fifth Rebuild of the Second CW Oscillator

	Pulsed	CW
Peak Output Power (kw)	82.7	37.1
Frequency (GHz)	27.895	27.874
Beam Voltage (kV)	68.1	70.3
Beam Current (A)	8.6	7.0
Efficiency (%)	14.1	7.54
Gun Anode Voltage (kV)	17.1	18.6
RF Pulse Duration (μs)	278	CW
Pulse Repetition Rate (pps)	421	CW
RF Duty (%)	11.7	CW
Average Power (kW)	9.68	37.1
Magnet Coil Currents (A)		
Main 1	427	444
2	497	489
3	500	490
4	562*	568*
Gun 1	8.6	10.2
2	11.0	10.7

*Main coil 4 was partially shorted. Effective current was less.

III. CW OSCILLATOR NO. 3

A. ORIGINAL BUILD

Five design changes were made for the third CW oscillator. An internal water load was added at the bottom end of the cavity to load spurious oscillations. A length change between the cavity and the first miter bend was made to decrease the effect of rotation of the miter bend on the shape of the resonance curve. The single disk beryllia output window was replaced with a double disk FC-75 face-cooled window. The VacIon® pump was moved from the top of the collector, where its body was at collector potential, to the output waveguide section assembly, where its body is at earth ground potential. The top of the collector was loaded by a 2.5" diameter waveguide, miter bend and single disk beryllia window to which an external water load could be attached.

The tube was tested on a pulsed basis to a power output level of 71.2 kw peak. The operating parameters are shown in Table 2. At the above power level 26.9 kw peak was also being absorbed in the internal water load. The total microwave power removed from the beam is at least equal to the sum of these two values. Such a large amount of power delivered to the internal load is considered unacceptable.

The introduction of the internal load and the change in guide length between the cavity and miter bend apparently changed the cavity Q resulting in the low efficiency measured on this tube.

Because of the low efficiency, it was not possible to evaluate any improvement in the FC-75 face-cooled window since the single disk version did not fail until 105 kW, CW.

The new position of the VacIon pump eliminated the need to isolate the electrical connections to the pump.

Some heating of the miter bend at the top of the collector was found to be caused by electron bombardment. An external water-cooled plate was added to the miter plate to remove that heat.

TABLE 2

Pulsed Operating Parameters for the Third CW Oscillator

Peak Output Power (kw)	71.2
Frequency (GHz)	28.006
Beam Voltage (kV)	78.7
Beam Current (A)	9.5
Efficiency (%)	9.52
Gun Anode Voltage (kV)	22.7
RF Pulse Duration (μs)	275
Pulse Repetition Rate (pps)	120
RF Duty (%)	3.3
Average Power (kW)	2.35
Magnet Coil Currents (A)	
Main 1	492
2	463
3	500
4	478
Gun 1	11.8
2	10.2

Spurious oscillations were observed at 26.828 GHz, 26.860 GHz, and 26.870 GHz.

B. FIRST REBUILD

The tube was rebuilt without the internal cavity load and after cold testing the cavity Q.

The highest peak output power observed during pulsed testing was 171 kw. At this level, 17.5 kw of peak power was also dissipated in the top water load. The highest average power obtained under pulsed conditions was 18.5 kW. CW testing was cut short by the failure of one of the main coil power supply transformers. However, CW start oscillation conditions were measured. The operating parameters at Varian for the first rebuild of the third CW oscillator are shown in Table 3.

TABLE 3

Pulsed Operating Parameters for the Rebuild of the Third CW Oscillator

Peak Output Power (kw)		147
Frequency (GHz)		27.975
Beam Voltage (kV)		79.9
Beam Current (A)		8.8
Efficiency (%)		20.9
Gun Anode Voltage (kV)		24.4
RF Pulse Duration (μs)		300
Pulse Repetition Rate (pps)		420
RF Duty (%)		12.6
Average Power (kW)		18.5
Magnet Coil Currents (A)		
Main	1	502
	2	481
	3	482
	4	496
Gun	1	11.5
	2	4.5

IV. ALTERNATIVE OUTPUT COUPLING SYSTEMS

A. MIRROR SYSTEM

A careful evaluation of the spherical mirror system, while carried out primarily on the TE_{01} mode, pointed out the critical mode suppression, spacing, and aligning requirements of the mirrors. While these requirements could be met in cold-test laboratory experiments, the problems associated with building a bakeable tube in which one of the mirrors (the second) would receive the existing dc beam with power densities in excess of 1 kW/cm^2 at its periphery led us to examine some other approaches which were mechanically simpler and which avoided the inevitable trapped reflections of the mirror system.

B. STRAIGHT-THROUGH COLLECTOR APPROACHES

The various straight-through (axisymmetric output) approaches that have been considered in some detail are:

1. 5" diameter collector, 5" diameter window, and 5" diameter output guide
2. 2.5" diameter collector, 2.5" diameter window, and 2.5" diameter output guide
3. 5" diameter collector, taper to 2.5" diameter window and 2.5" diameter output guide

1. 5" Diameter Collector, Window, and Output Guide

A paper design for this type of collector/output was completed and is shown schematically in Figure 1. This consisted of an 8° taper from the TE_{021} cavity to the 5" diameter collector. Beam trajectory calculations showed that a short additional magnet coil could bring the maximum of the beam power density to the region of the transition from the taper to the cylinder. The beam was thus spread over a larger area reducing the actual power density at the wall by as much as a factor of two close to the transition. A transverse magnet providing a field of greater than 300 gauss isolated the window from secondary electrons. The length of the output section from the top of the

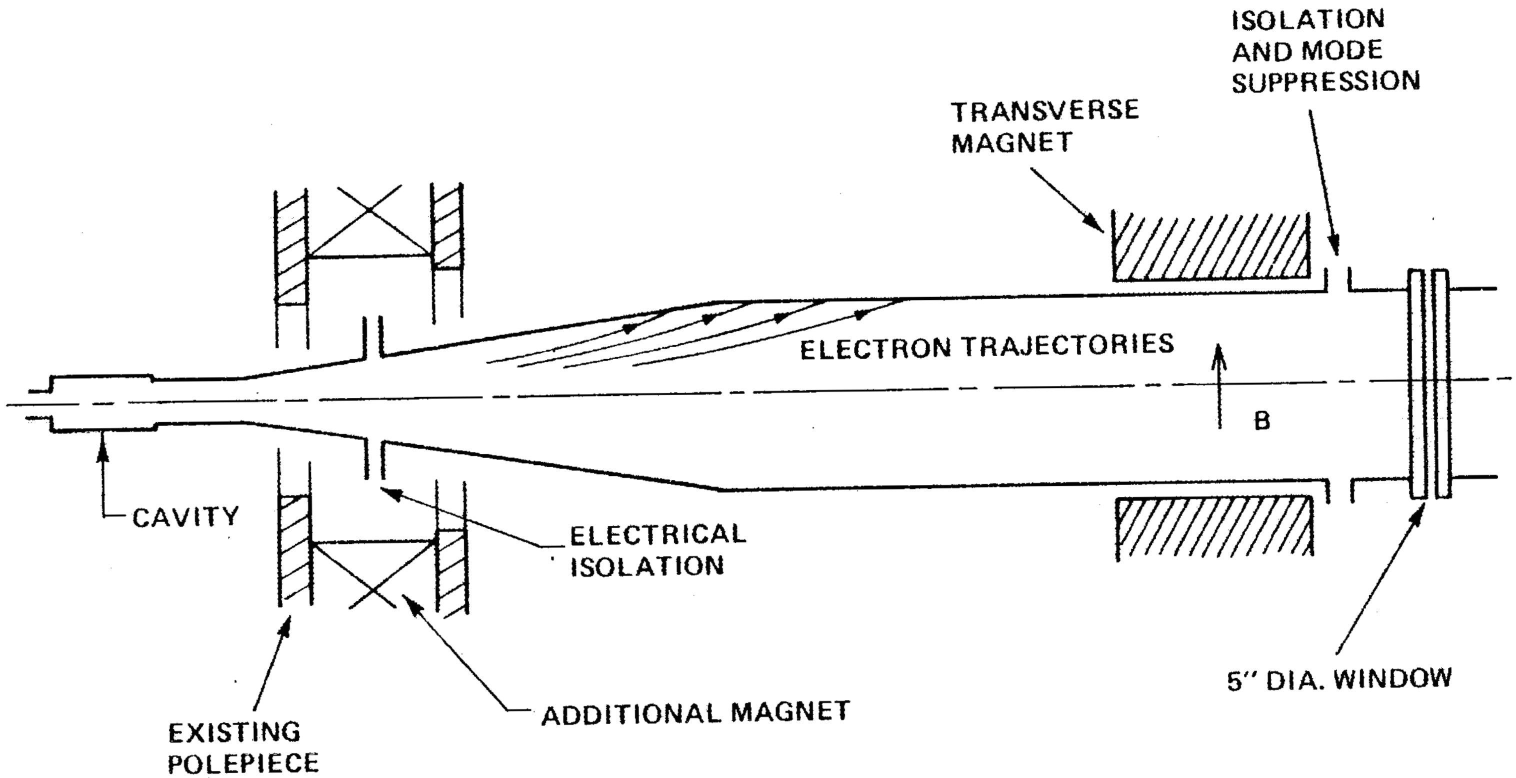

FIGURE 1. 5" DIAMETER COLLECTOR, WINDOW, AND OUTPUT GUIDE

existing polepiece to the window was 40". A paper design was also completed for a double FC-75 face-cooled 5" diameter window. To withstand the atmospheric and coolant combined pressure, the thickness of each of the 5" diameter windows must be increased to at least one guide wavelength per window. The increased window thickness would result in proportionally larger microwave power loss. From the point of view of thermal conductivity to the face of the window, the diameter is not important, because the larger power loss and the increased thickness are offset by the increased area available for face cooling. With respect to the interface between the window and the coolant, the larger window has some advantage since the power per unit area is reduced.

The obvious advantage of this approach is the increased collector diameter which makes beam spreading less critical. The window has increased power loss but reduced interface cooling density. The 5" output guide could be used, but there are clearly practical inconveniences and difficulties due to the large size. Overall, the approach does not appear to be optimum.

2. Design of a 2.5" Diameter Collector/Output

The design of a 2.5" ID collector is critically dependent upon the control of the electron beam, particularly the dc beam, in the collector. From a knowledge of the magnetic flux threading the cathode and the magnetic field and electron velocity components in the interaction region, it can be shown that when the beam is at the collector radius, adequate magnetic flux for its control is still provided. The beam is expanded adiabatically into the collector. This will occur if there is a sufficiently gradual reduction in magnetic field in the collector. In the interaction region, the maximum space-charge force associated with the dc beam is less than 0.4% of the magnetic force. At the collector wall, the space-charge force on the outer electrons increases to about 10% of the radial magnetic force. This means that for a real beam, outer electrons will be intercepted by the collector earlier than would be the case for zero space charge. Inner electrons would arrive at the collector at points closer to space-charge-free calculation. Thus, the effect of space charge is to give a modest reduction in the power density at the collector wall. Calculations based on space-charge-free conditions will thus be conservative.

Trajectory calculations were carried out in analytic magnetic fields that could be synthesized by long low-power solenoids. The fields had the form $B_z = a/(b + Z)$ where a and b are constants. This form of field enabled the field to be reduced by a factor g in a distance λ_c, computed on the basis of B_{z1}, at axial position Z_1. Calculations showed that the beam expansion was satisfactorily adiabatic for values of g ($g = \Delta B/B$) as high as 0.5 (i.e., the magnetic field falls to half its initial value in a distance corresponding to the cyclotron wavelength based upon the magnetic field at the initial position). At fields below 1000 gauss the axial velocity remains constant to 4%, and thus g was essentially constant in this important region.

Figure 2 shows the interception of inner trajectories at the collector wall. Nine electrons were introduced equispaced around a circular cross section of a cycloidal orbit. Their transverse and axial energies corresponded to the magnetic field at the plane of introduction. Similar trajectories for outer electrons are intercepted in a shorter distance translated by about 6" towards the cavity. From the summation of such sets of trajectories, the current density at the collector can be determined. This takes the form shown in Figure 3. The magnetic field for this case is shown in Figure 4. Note that the maximum power density (under dc conditions) into the collector would be ~ 1 kW/cm^2. Collector power density distributions were estimated for a variety of modes of operation. In all cases, the maximum power density was less than 1.25 kW/cm^2. To prevent excessive movement of the beam in the collector as the gun coil currents are adjusted, it was planned to program the collector magnet such that the collector magnet current $I_c \propto 9 + I_{G1}$ where I_{G1} is the current of gun coil Number 1.

The complete collector is shown in Figure 5. A 3.5° taper extends from the cavity to the 2.5" diameter. This is followed by an insulated gap which enables body current to be measured and also acts as a mode suppressor for non-TE_{on} modes. The collector is cooled by 36, 0.187" diameter cylindrical channels with a water flow of 200 gpm requiring a pressure head of 180 psi. A transverse magnetic field of greater than 600 gauss provides a barrier for high energy secondary electrons. The window would be mounted in line so that external mode suppression (external to the vacuum tube) could be provided between the window and the first miter bend of the output guide. Mode con-

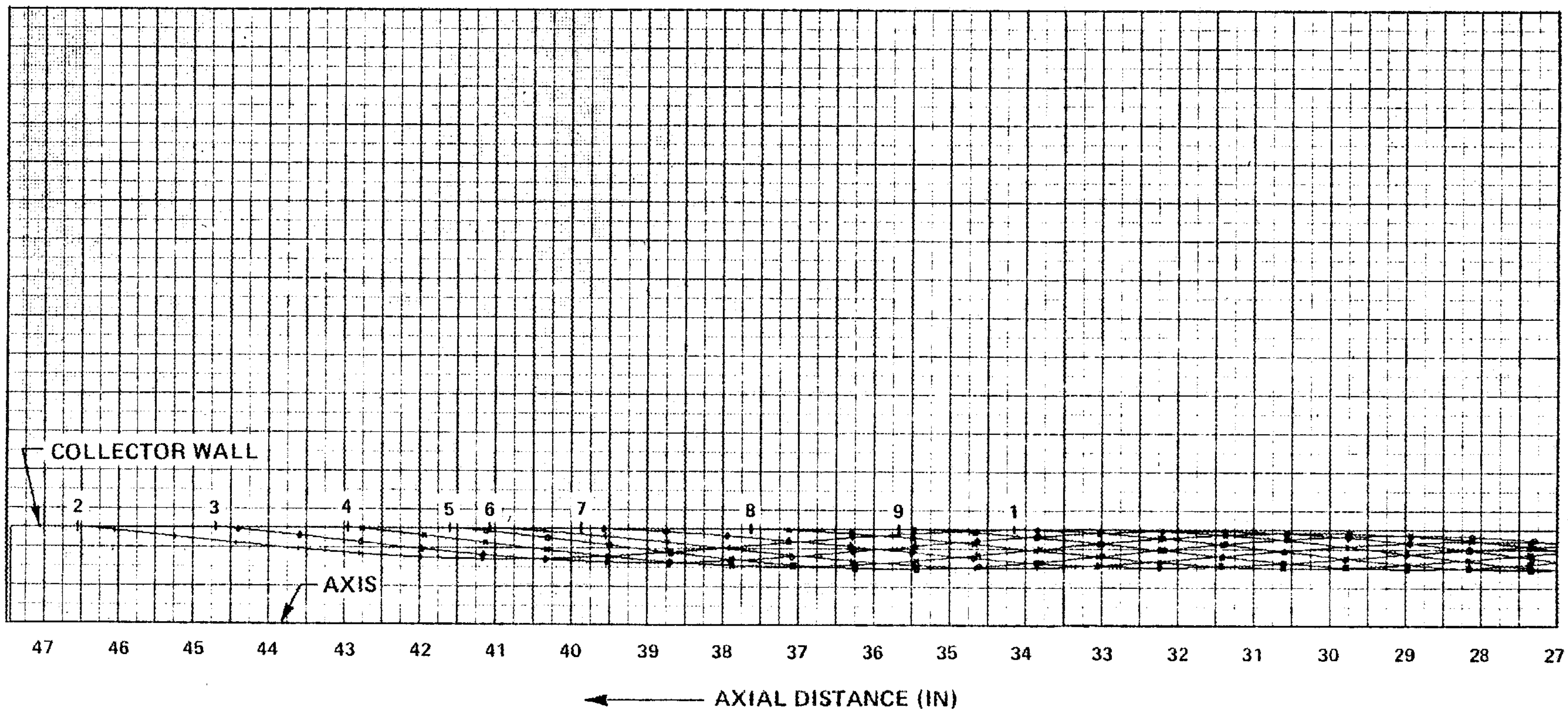

FIGURE 2. DISTRIBUTION AT 2.5" DIAMETER COLLECTOR WALL OF ELECTRONS FROM FRONT OF CATHODE

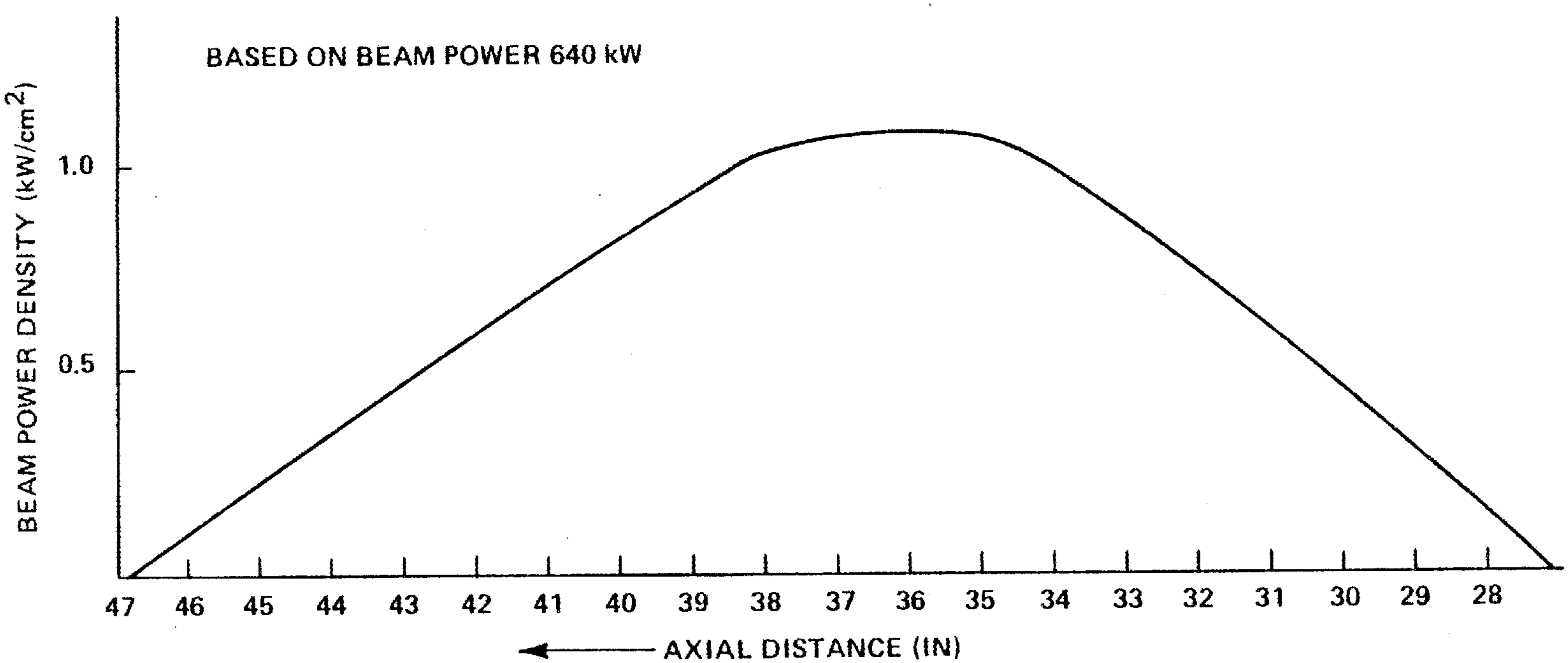

FIGURE 3. DC BEAM POWER DENSITY AS FUNCTION OF DISTANCE ALONG COLLECTOR

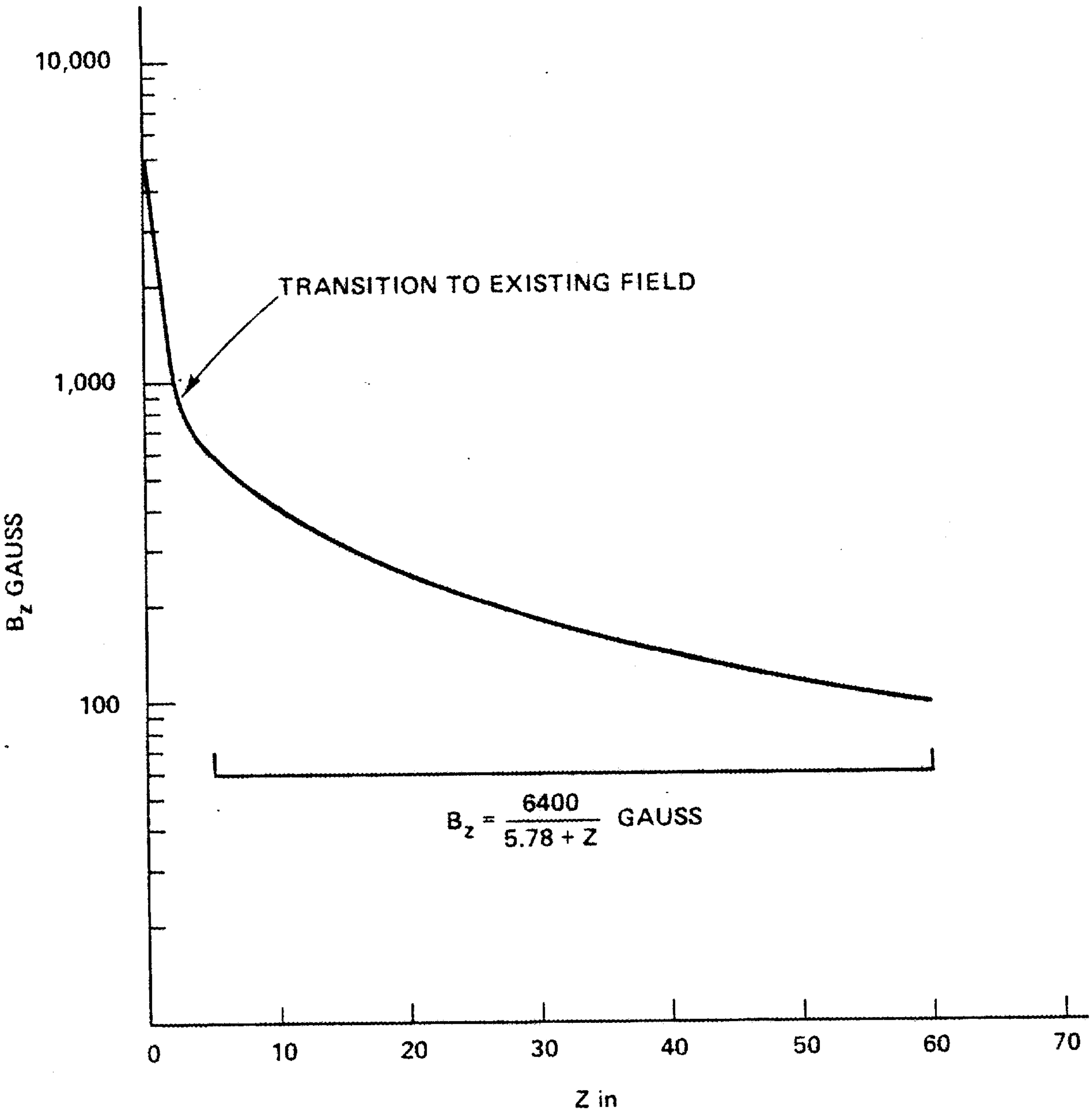

FIGURE 4. MAGNETIC FIELD FOR TRAJECTORIES OF FIGURE 2

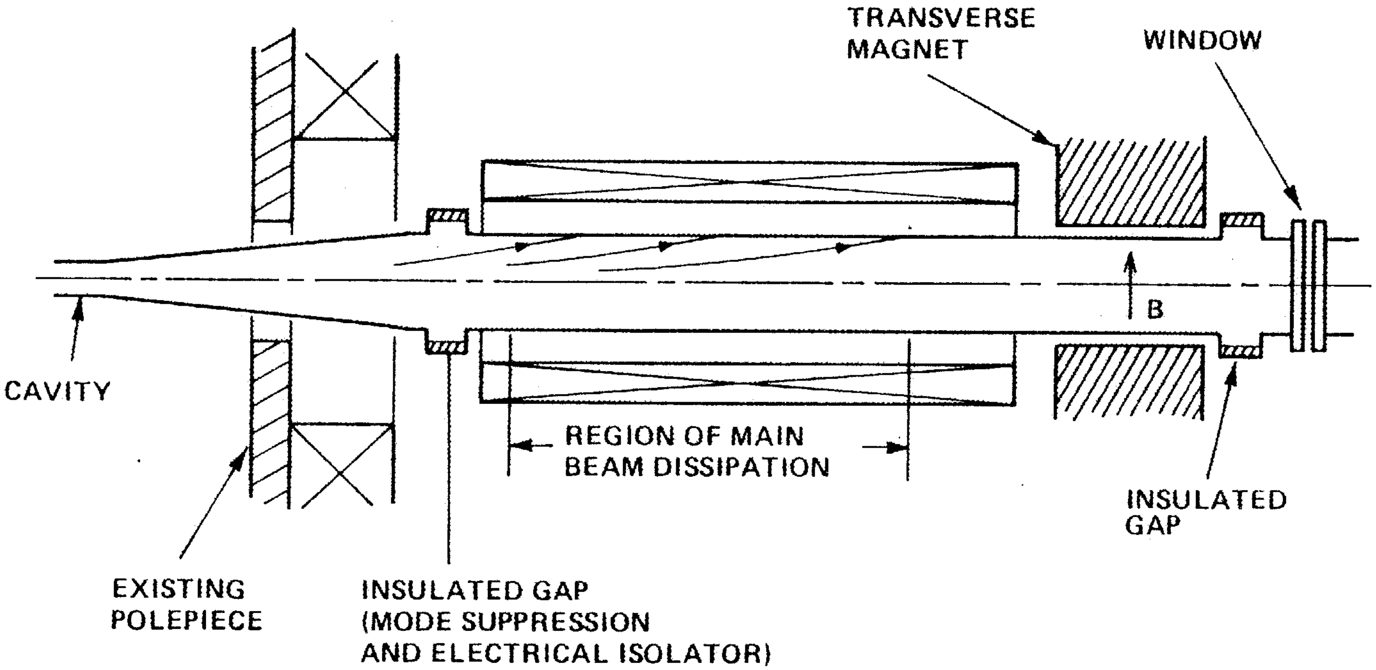

FIGURE 5. 2.5" DIAMETER COLLECTOR, WINDOW, AND OUTPUT GUIDE

version from the TE_{02} to other circular-electric modes would be less than 5% (power basis).

Estimates were made of the required tolerances on the collector alignment with respect to the beam containing flux tubes. These were practical. However, the recent examination of minor beam damage in a 10" diameter collector indicates considerable lack of axial symmetry in the guiding flux tubes through the main magnet at ORNL. While detailed calculations have not been made of such an asymmetry on the 2.5" diameter collector, such asymmetry is clearly undesirable, outside acceptable tolerances, and must be reduced to make this approach practical.

3. 5" Diameter Collector with Taper Down to 2.5"

This system should have more tolerance with respect to beam position than the 2.5" diameter collector. It is planned that electron trajectory calculations will be made to study this possibility. The other question to be answered is whether tapering the output guide back down to 2.5" diameter can be accomplished without excessive mode conversion. Cold-test hardware has been designed and is being constructed to test the effects of the taper.

V. PROGRAM SCHEDULE AND PLANS

The updated milestone chart is shown in Figure 6. The initial construction of tube No. 3 was completed in accordance with the previous schedule; however, the performance of the tube necessitated a rebuild. The rebuilding and retesting period is indicated on the chart. This led to an initial shipping date at the end of September.

During July, an unscheduled rebuild of tube No. 2 was also accomplished. This was added to the milestone chart.

The performance of tube No. 3 was not sufficiently good to warrant completion of tube No. 4 using the same design. Therefore, the planned completion of No. 4 has been rescheduled to October. This will allow further consideration of alternative configurations for coupling out microwave power. It is expected that investigation of alternative output systems will be continued through the next quarter, even beyond the completion of tube No. 4.

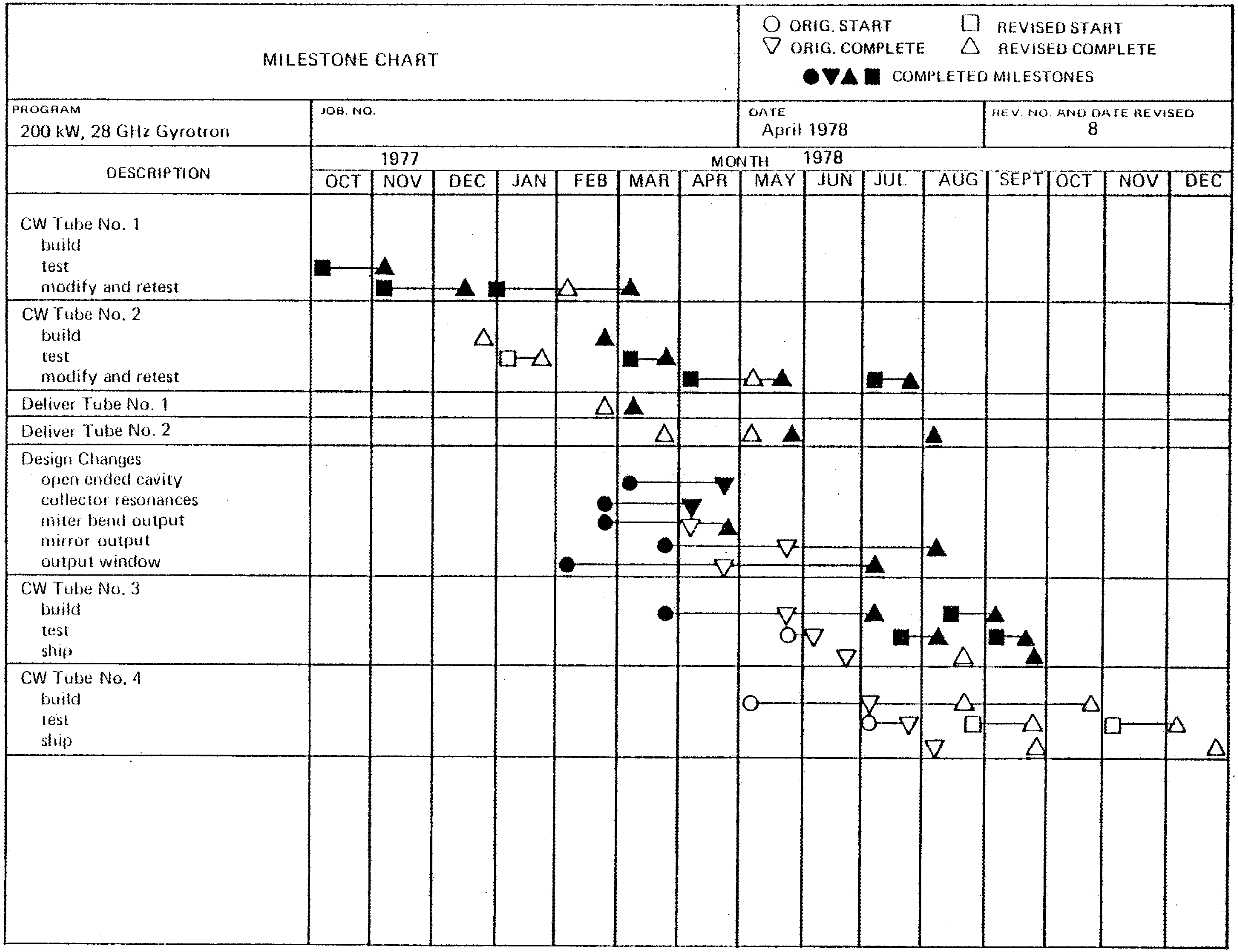

FIGURE 6. MILESTONE CHART

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