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DEVELOPMENT PROGRAM FOR A 200 kW, CW GYROTRON

J. J. Tancredi, M. Caplan, J. J. Sandoval,
V. A. Matranga

QUARTERLY REPORT NO. 10
OCTOBER THROUGH DECEMBER 1981

Report Prepared by

HUGHES AIRCRAFT COMPANY
Electron Dynamics Division
3100 West Lomita Boulevard
Torrance, California 90509
under
Subcontract No. 53Y-33200C

for
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. DEPARTMENT OF ENERGY
Contract No. W-7405-eng-26

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ABSTRACT

The objective of this program is the design and development of a millimeter wave device to produce 200 kW of continuous-wave power at 60 GHz. The device, a gyrotron oscillator, will be compatible with power delivery to an electron-cyclotron plasma. Smooth control of RF power output over a 17 dB range is required, and the device should be capable of operation into a severe time-varying load mismatch.

During this report period, an analysis of tests on the first gyrotron, S/N 1, was undertaken. In order to understand the mechanism by which a frequency of 3.5 GHz could be emitted from the gun end of the tube, detailed gun tests were performed on S/N 1. These are compared to tests on a previously-built gun tester.

In addition a rationalization of the high azimuthal mode content from S/N 1 is also presented.

Progress continued on the electrical check-out of a 100 ms pulse modulator.

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LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

The objective of this program is the design and development of a millimeter-wave device to produce 200 kW of continuous-wave power at 60 GHz. The device, a gyrotron oscillator, will be compatible with power delivery to an electron-cyclotron plasma. Smooth control of rf power output over a 17 dB range is required, and the device should be capable of operation into a severe time-varying rf load mismatch. An an interim goal, demonstration of gyrotron performance with 100 ms pulses is required.

The technical baselines for the gyrotron and the associated power supply are shown in Table I. Using the gyrotron shown schematically in Figure 1-1, a magnetron-injection electron gun forms the electrons into a hollow beam putting a considerable amount of their energy in rotation (Figure 1-2). A gradually rising magnetic field (Figure 1-3) from a superconducting solenoid compresses the beam in diameter while increasing the orbital energy according to the theory of adiabatic invariants until approximately 3/4 of the beam energy is in rotation, and the rotational frequency is 60 GHz. The magnetic field becomes uniform at this point and the beam enters a quasi-optical open cavity where the spinning electrons interact with the eigen mode of the cavity (Figure 1-4). The rf energy builds up at the expense of the rotational energy of the dc beam (Figure 1-5). The spent beam enters the region of decreasing magnetic field, undergoes decompression and impinges on the collector (Figure 1-6). The latter also functions as the output waveguide. To handle the power in the spent beam and the power dissipation in the window, the output waveguide tapers up from the cavity diameter to an appropriate value (Figure 1-7).

During this quarter, progress was made toward determining the source of an oscillation emitted from the gun end of S/N 1. Detailed tests were made comparing gun performance of S/N 1 with a previously constructed gun tester.

A preliminary evaluation of the cause of high output power in other modes was also completed.

Progress was also made on a revised cavity design and the electrical check-out of a 100 ms modulator.

TABLE I

The Gyrotron	
Frequency	60 GHz
Power out	200 kW RF
Electronic efficiency	35%
Beam voltage	70-80 kV
Beam current	7.0 A - 8.0 A
Modulation voltage	23 kV
Magnetic field	23.0 kG
Transverse to longitudinal velocity ratio	1.5 - 2.0
The Power Supply	
Voltage rating	100 kV dc
Current rating	10 A
Anode supply voltage	0-35 kV dc
Anode supply current	<20.0 mA
Heater supply voltage	0-15 V, ac
Heater supply current	15 A
Operating Modes:	
1.	10 μs pulse length
2.	1 ms - 100 ms pulse length
3.	30 s to cw

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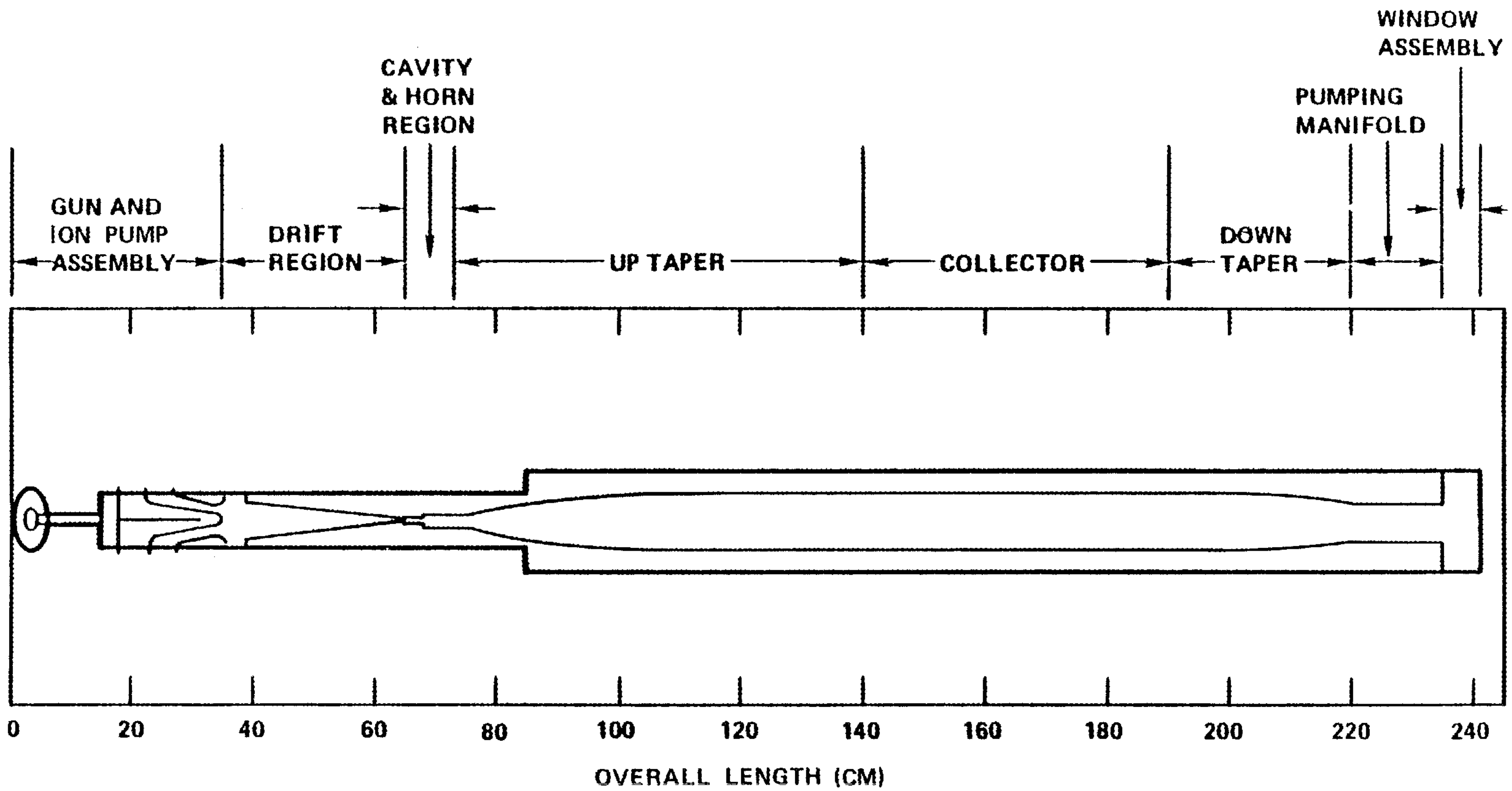

Figure 1-1   917H S/N 1 gyrotron layout.

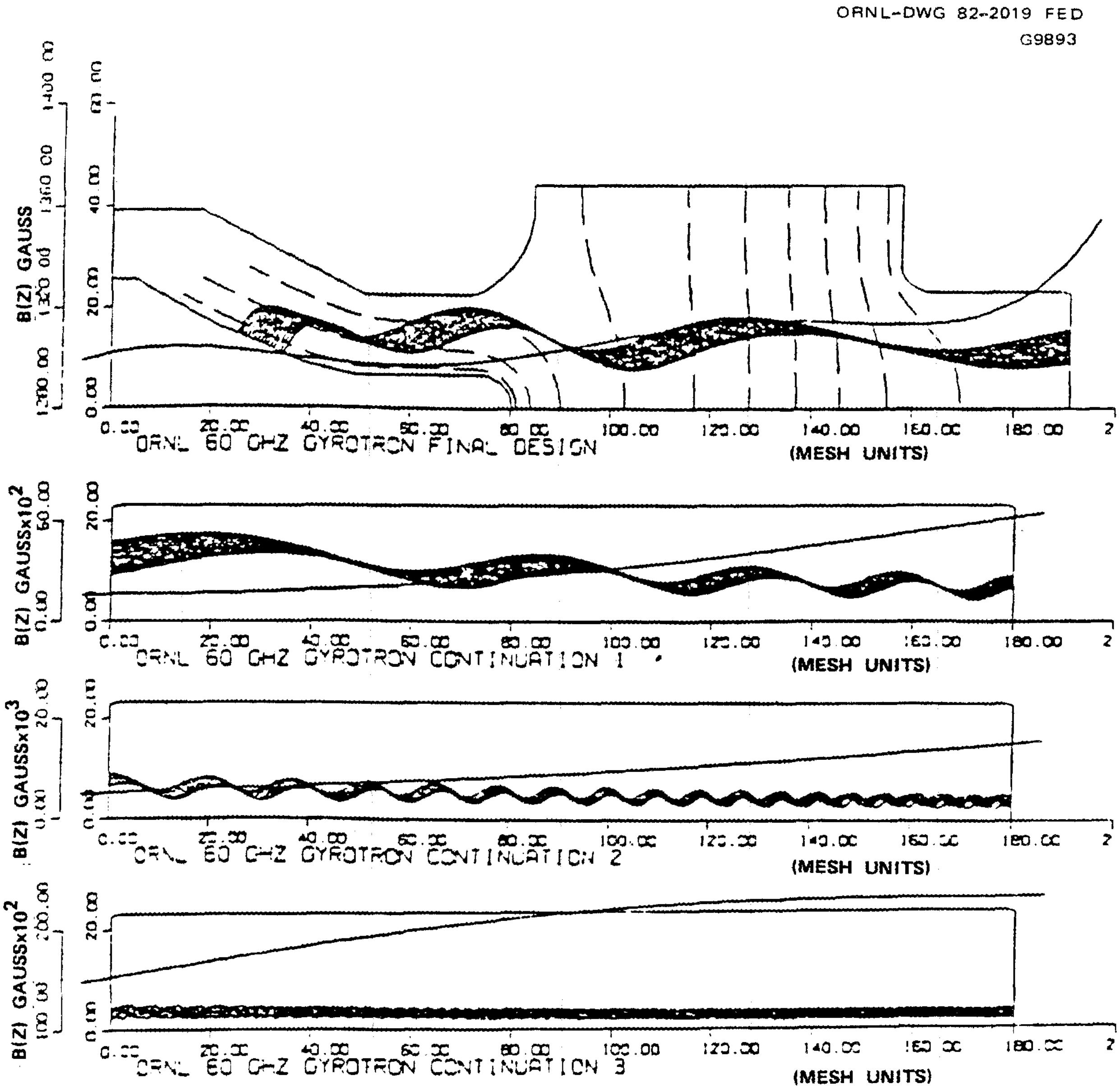

Figure 1-2 Final magnetron injection gun and magnetic field configurations.

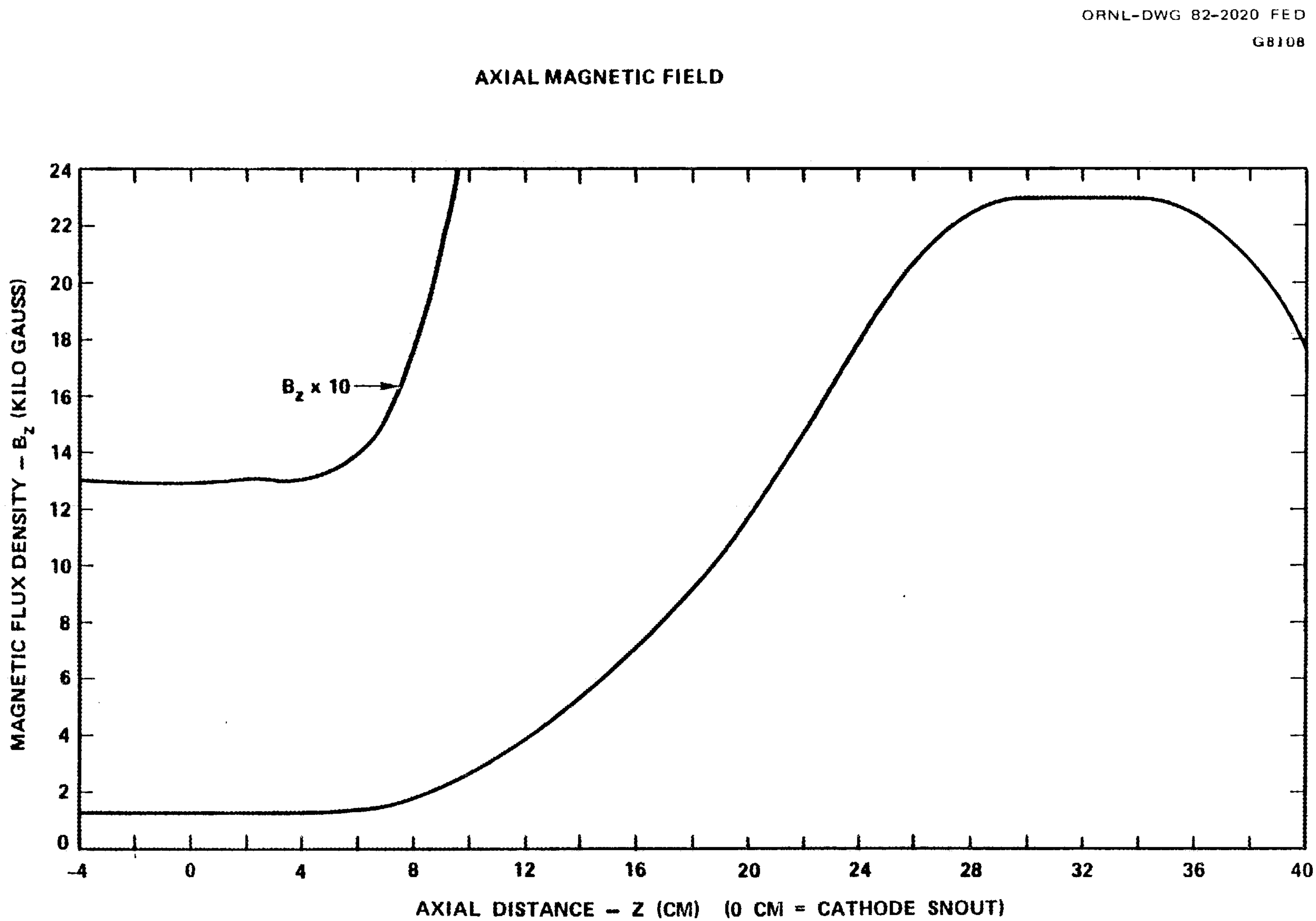

Figure 1-3 Axial magnetic field for ORNL 60 GHz gyrotron.

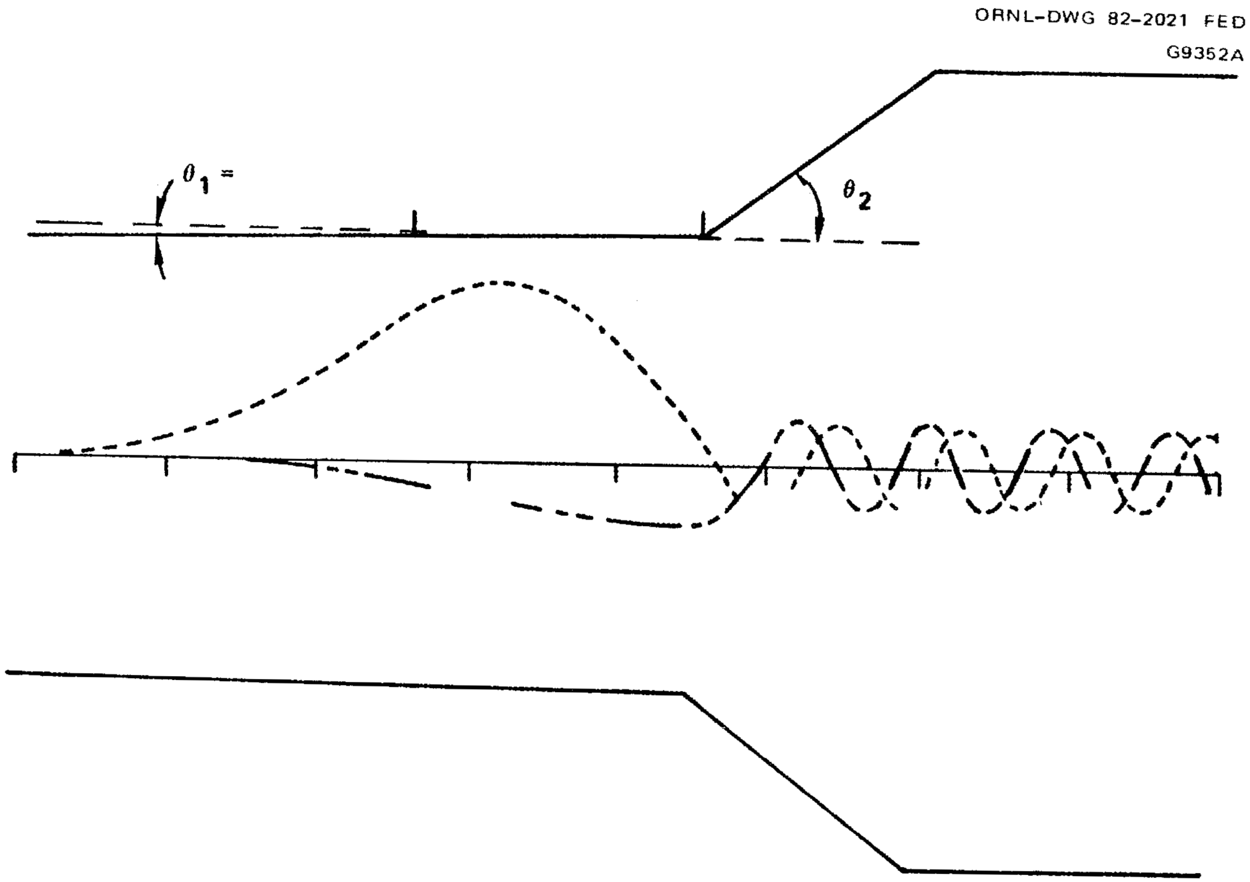

Figure 1-4   Cavity configuration.

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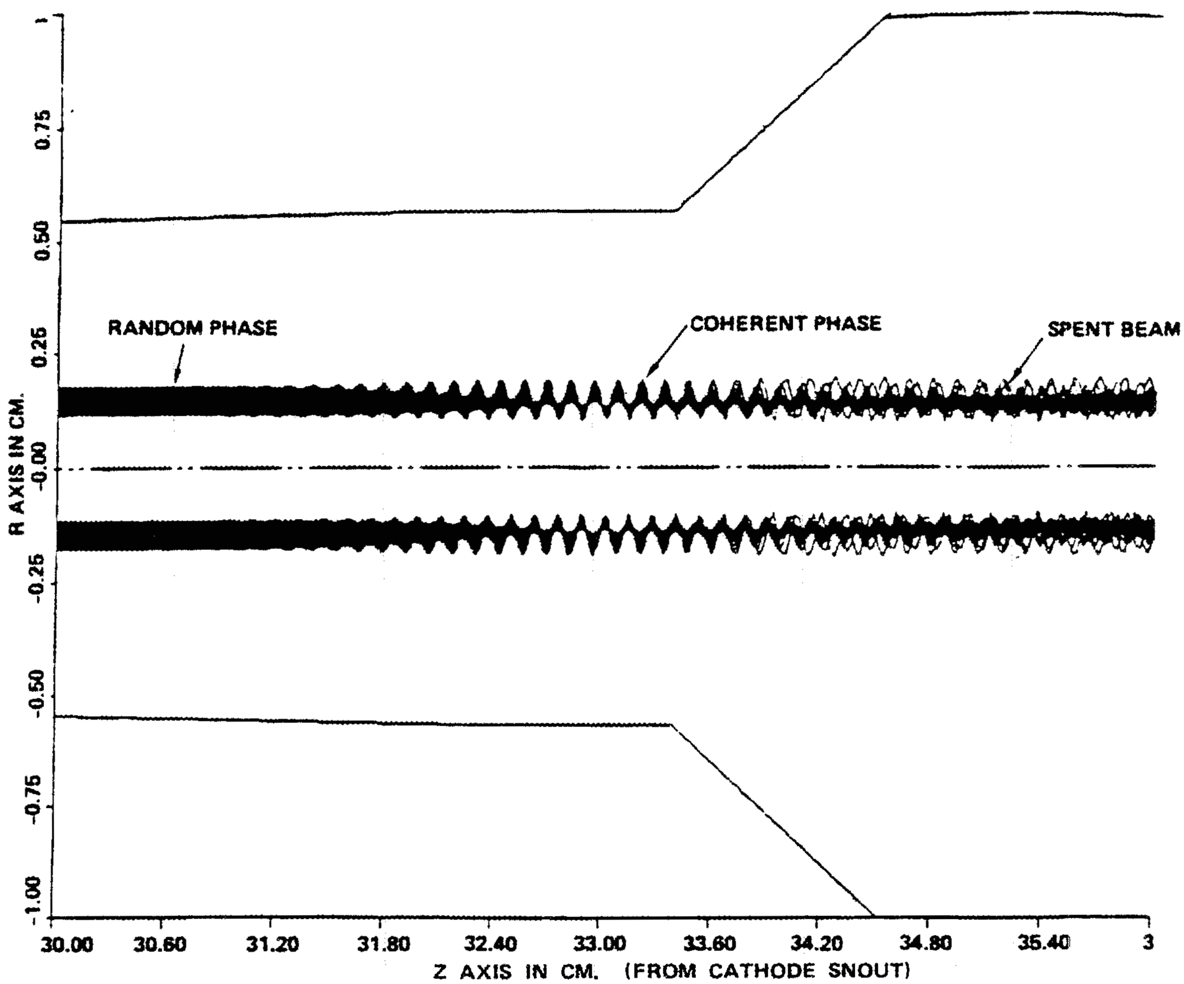

Figure 1-5 Phase bunching of hollow electron beams.

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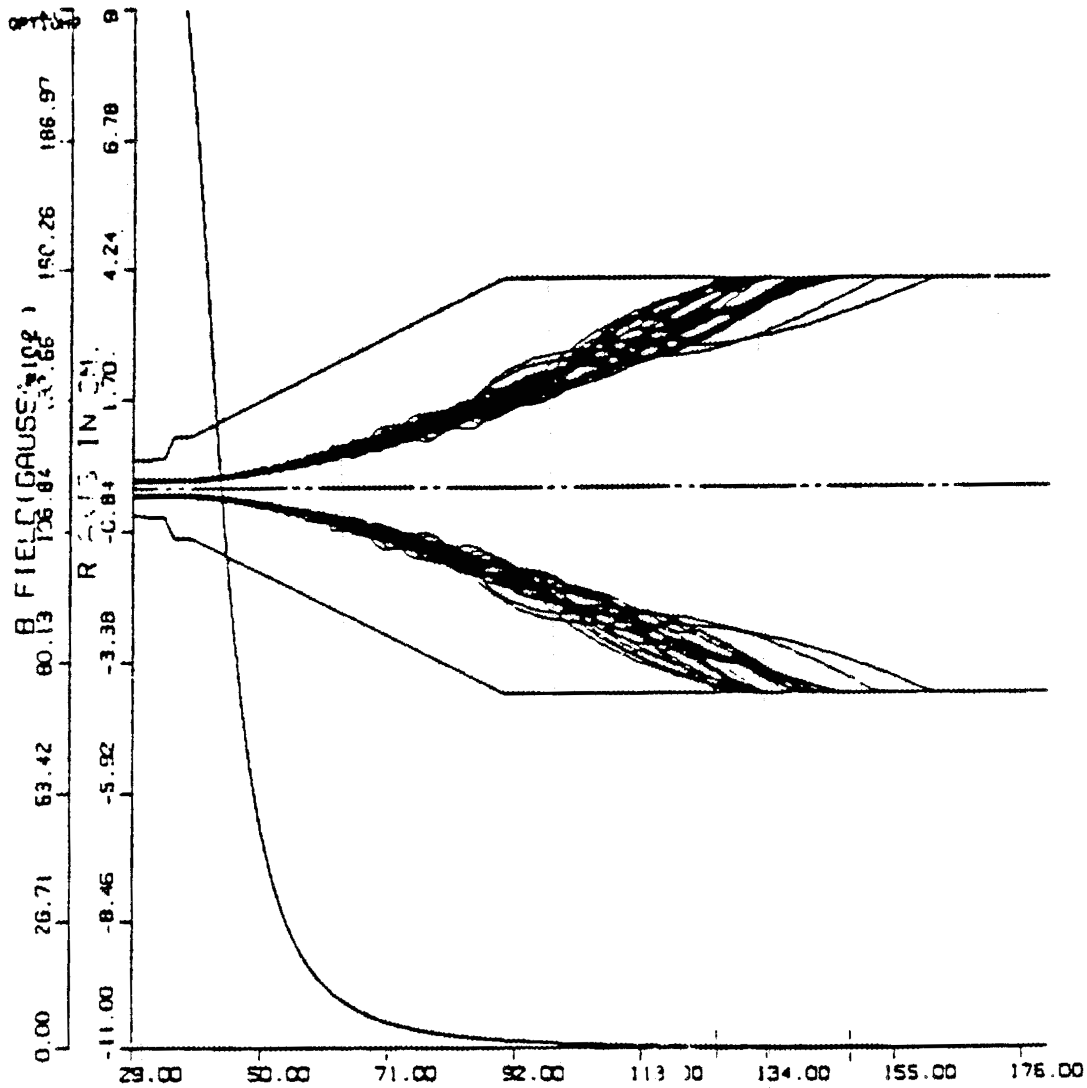

Figure 1-6 Graphic plotter output of an electron beam RF modulated by a cavity, and impacting on the collector walls.

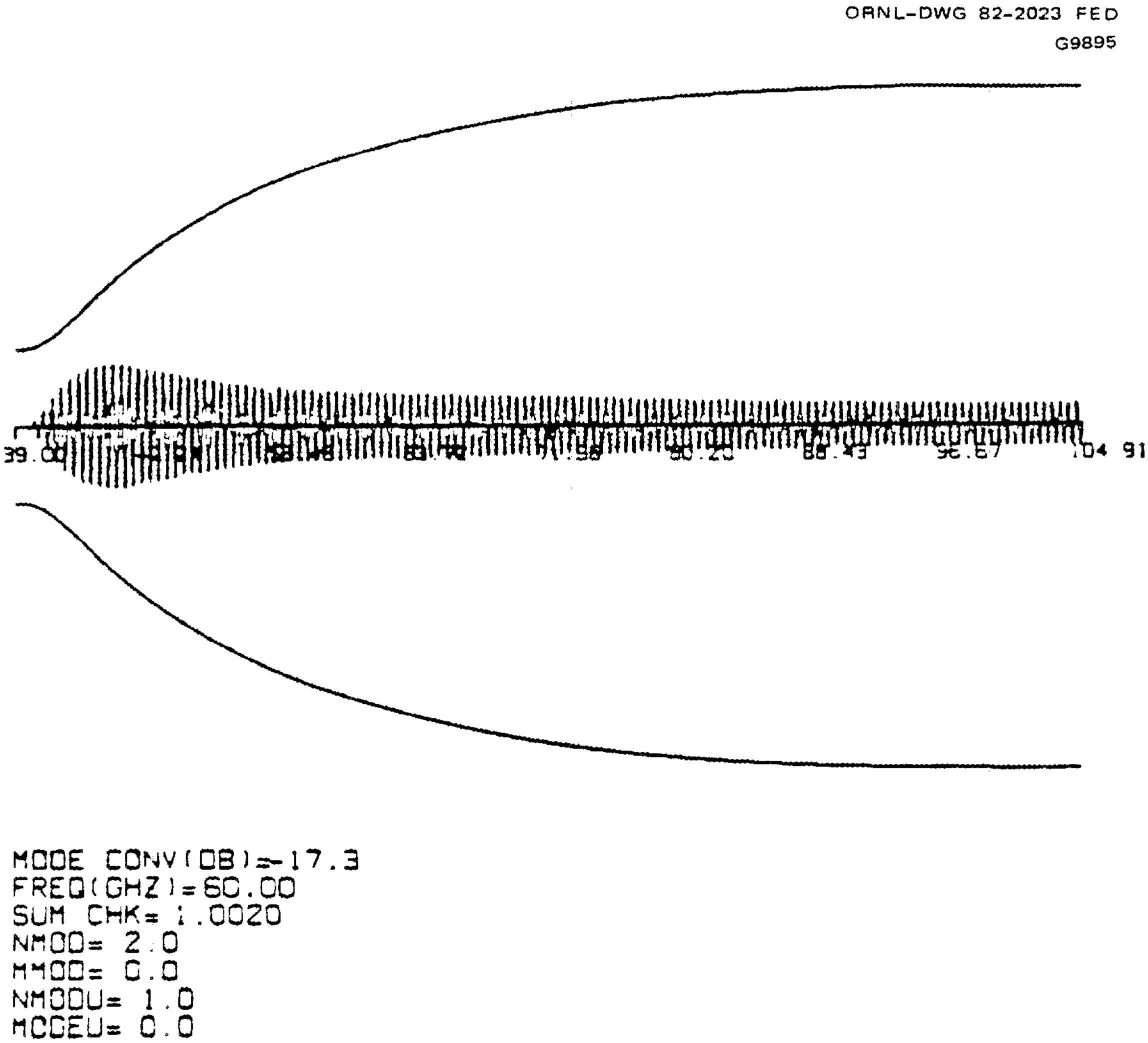

Figure 1-7 Raised cosine taper for the ORNL gyrotron, with the TE_{01} mode suppressed 17.3 dB.

2.0 PROGRESS

2.1 GENERAL

During this report period technical effort was devoted to furthering the understanding of problems which occurred on S/N 1. These problems were twofold:

- Beam instability - high mod-anode interception.
- Spurious modes - those with high azimuthal index.

In addition to investigation of the above problem areas, a revised cavity design for S/N 1A was completed. Progress was also made on the 100 ms modulator.

2.2 BEAM INSTABILITY

As indicated in the previous report[1] and summarized here, anomolous behavior of mod-anode interception was noted during tests of S/N 1, compared to prior evaluation of a gun tester.[2] The gun tester is a sealed-off gun assembly which was evaluated in a conventional solenoid. The solenoid produced a 1300 gauss flat axial field, which is the design configuration for magnetic field in the gun region, as shown in Figure 1-3 for $Z < 0$. Under these circumstances mod-anode interception in the gun tester was negligible.

During tests of S/N 1, however, with an identical gun magnetic field produced by a superconducting solenoid, and with an identical gun, mod-anode interception was disturbingly higher. Two distinctly separate modes of interception were noted:

a. Higher mod-anode interception at anode voltages above 18 kV.

b. At anode voltages above 11 kV, sudden increases in mod-anode interception were observed which corresponded with an oscillation emanating from the gun at a frequency near the cyclotron frequency of the gun region ($\simeq$ 3.5 GHz).

Diagnostic effort during the latter portion of the last quarter eliminated the possibility that the gun-end oscillation was attributable to a physical resonance in the gun structure, since the oscillation was magnetically tunable over more than an octave range, whenever a flat axial field was used in the gun region. Moreoever, the oscillation could be eliminated by using a rapidly increasing, tapered magnetic field. Therefore, the gun-end oscillation appears to be a beam instability as opposed to a gun oscillation.

During this quarter, a plan was devised to evaluate the cause of high mod-anode interception and the beam instability. Tests to be implemented include:

- Evaluation of the gun tester in the superconducting solenoid.
- Cold test evaluation of the lossy drift section between the gun and cavity.
- Hot test of the gun tester with the lossy drift section added.
- Continued gun evaluation of S/N 1.
- Detailed magnetic field probing of the superconducting solenoid.

In this report, gun tester operation in the superconducting solenoid is compared with results from S/N 1.

Evaluation of the lossy drift section is planned in order to determine the amount of RF leakage from the cavity back toward the gun. Detailed magnetic field measurements of the solenoid are considered necessary because no in depth evaluation has been made since the solenoid was repaired by the manufacturer and returned to Hughes.[2]

2.2.1 Gun Tester Evaluation

A special fixture for suspending the gun tester in the superconducting solenoid was fabricated. The gun tester was mounted in the same position within the solenoid as the gun of S/N 1. Measurement of mod-anode interception is shown in Figure 2-1, and is compared with S/N 1. The magnetic field used is the "design" configuration shown in Figure 1-3, and is the same for both cases. The normal operating mod-anode voltage is 18 to 24 kV.

As can be seen from Figure 2-1, S/N 1 has an order of magnitude more interception than the gun tester, for the same test conditions. Below 10 kV, interception is $\leq$ 5 mA for both the gyrotron and the gun tester. At 11 kV and above, however, the beam instability is occurring in the gyrotron, as evidenced by the rapid rise in mod-anode interception. In addition, an oscillation at a frequency of approximately 3.5 GHz can be detected by a sensitive receiver-antenna pointed at the gun. The gun tester, on the other hand, does not manifest a rapid interception increase, nor can any beam instability be detected.

From this test, it is concluded that the beam instability is not attributable to the gun directly, but from another part of the tube. The next phase of this evaluation will be to add the next gyrotron assembly to the gun, the lossy drift section, which is comprised of a series alternating metallic and lossy beryllia rings. This test will be completed during the next quarter.

2.2.2 Superconducting Solenoid

Figure 2-1 has shown the mod-anode interception obtained with the gun tester focused by the superconducting solenoid. This performance differs considerably with that obtained in a room temperature solenoid, and reported previously.[2] The results of these two tests are compared in Figure 2-2.

In the room temperature solenoid, no interception is discernible up to 20 kV. This measurement is limited to about 1 mA by the toroidal current transformers employed for these short pulse (15 μs) tests. The fact that there is worse interception in the superconducting solenoid leads to the possibility that the transverse field of this solenoid may be affecting gun performance.

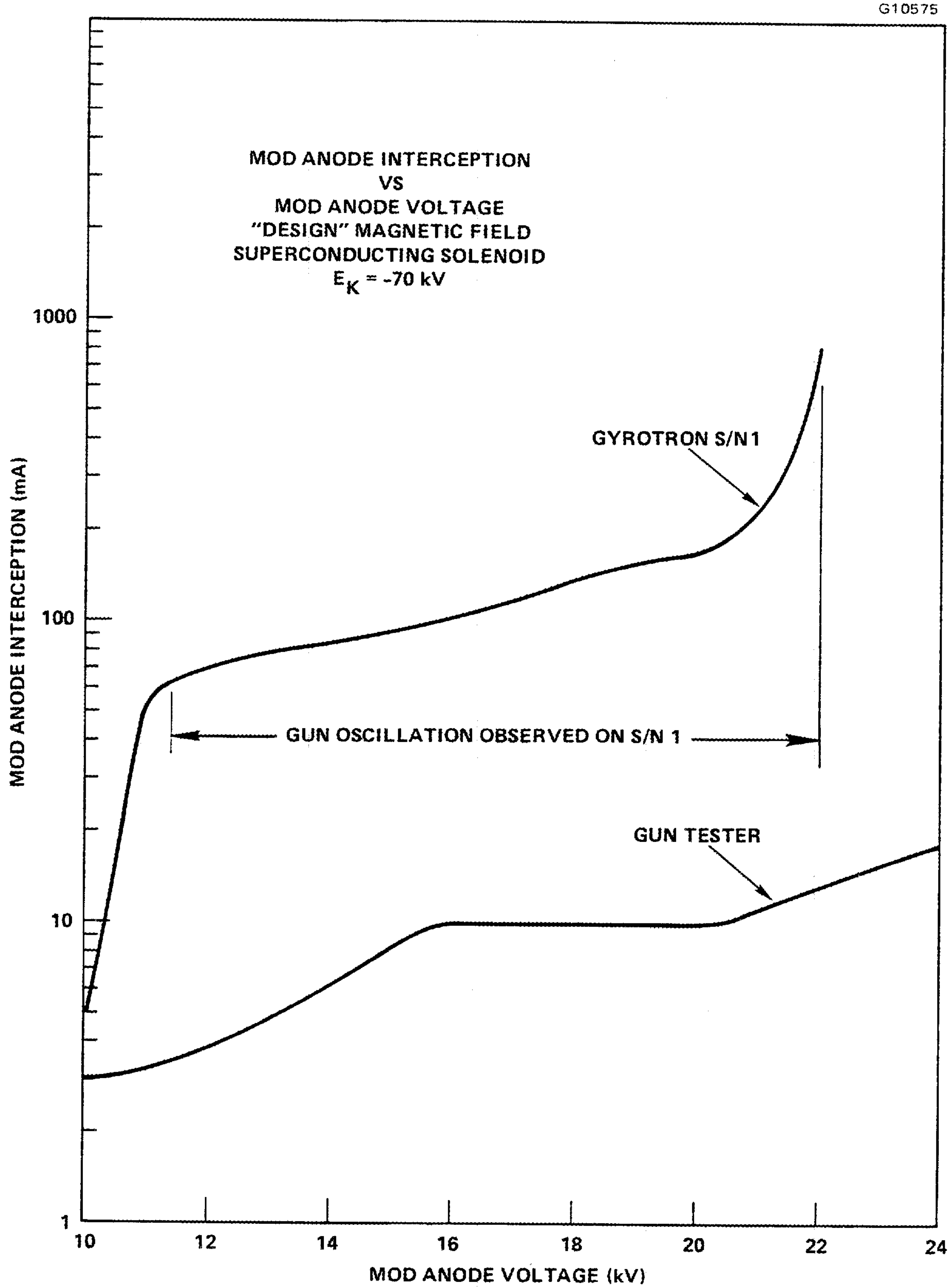

Figure 2-1 Comparison of mod-anode interception for the gun tester and S/N 1 in the superconducting solenoid.

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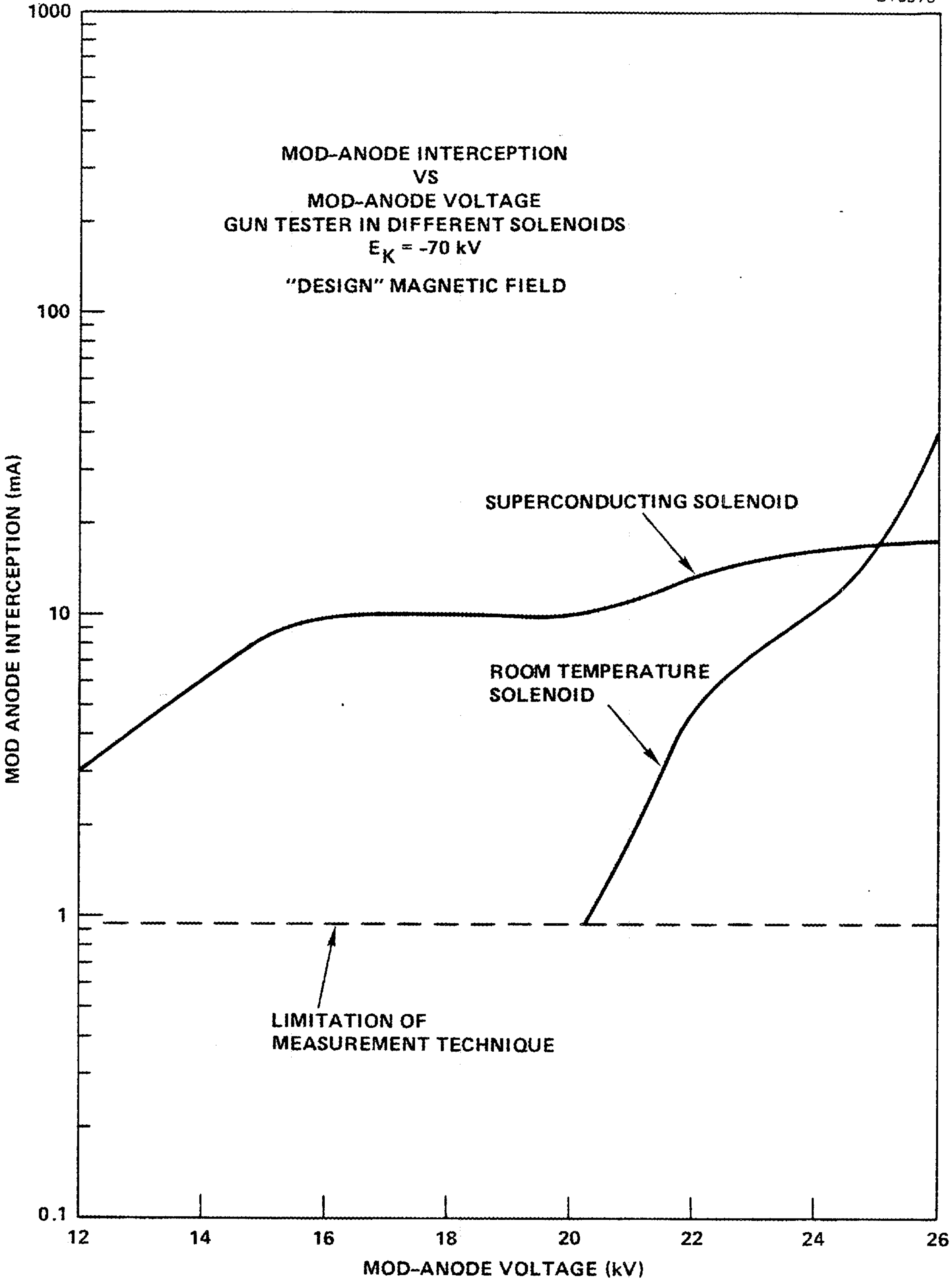

Figure 2-2 Comparison of mod-anode interception in the gun tester for different solenoids.

It should be noted that the present tube configuration is such that only 0.025" of radial movement is possible in the superconducting solenoid. The present position of the gun with respect to the solenoid is that for optimum RF performance of the gyrotron S/N 1, which attained 112 kW of power, much less than the 200 kW desired. Tube performance may have been limited by poor alignment of the tube with the magnetic axis.

For this reason, accurate axial and transverse field measurements of the superconducting solenoid are planned for the next quarter. Alignment fixtures have been ordered which will permit probing off the geometric axis of the warm bore.

2.2.3 Gyrotron S/N 1

The beam instability has been observed whenever a flat (no B_r component) magnetic field is used in the gun region of the gyrotron, but not in the gun tester. When the gun magnetic field is rapidly tapered, no evidence of an instability is noted. Also, for the tapered field case, mod-anode interception is considerably reduced. Figure 2-3 illustrates S/N 1 mod-anode interception for the case of a flat magnetic field compared with a tapered magnetic field over the gun region.

Figure 2-3 shows the dramatic improvement in beam interception obtained by using a tapered magnetic field in the gun. In the mod-anode voltage range from 18 to 21 kV, reasonable pulsed RF measurements could be made without loading down the cathode-modulated power supply with excessive current through the mod-anode divider network. The tapered magnetic field is, in fact, the field configuration used for all the RF data obtained to date.

One further test was performed in order to better characterize the beam instability and high mod-anode interception problem. This test consisted of operating S/N 1 with the "design" (flat) magnetic field in the gun, but terminating the magnetic field in the lossy drift region, thereby preventing the beam from entering the cavity. Figure 2-4 compares mod-anode interception for this test with the case where the "design" magnetic field is used throughout the tube. (The magnetic field is terminated by turning off the cavity coils and compensating the gun coils to produce a flat field, as determined by computer calculations).

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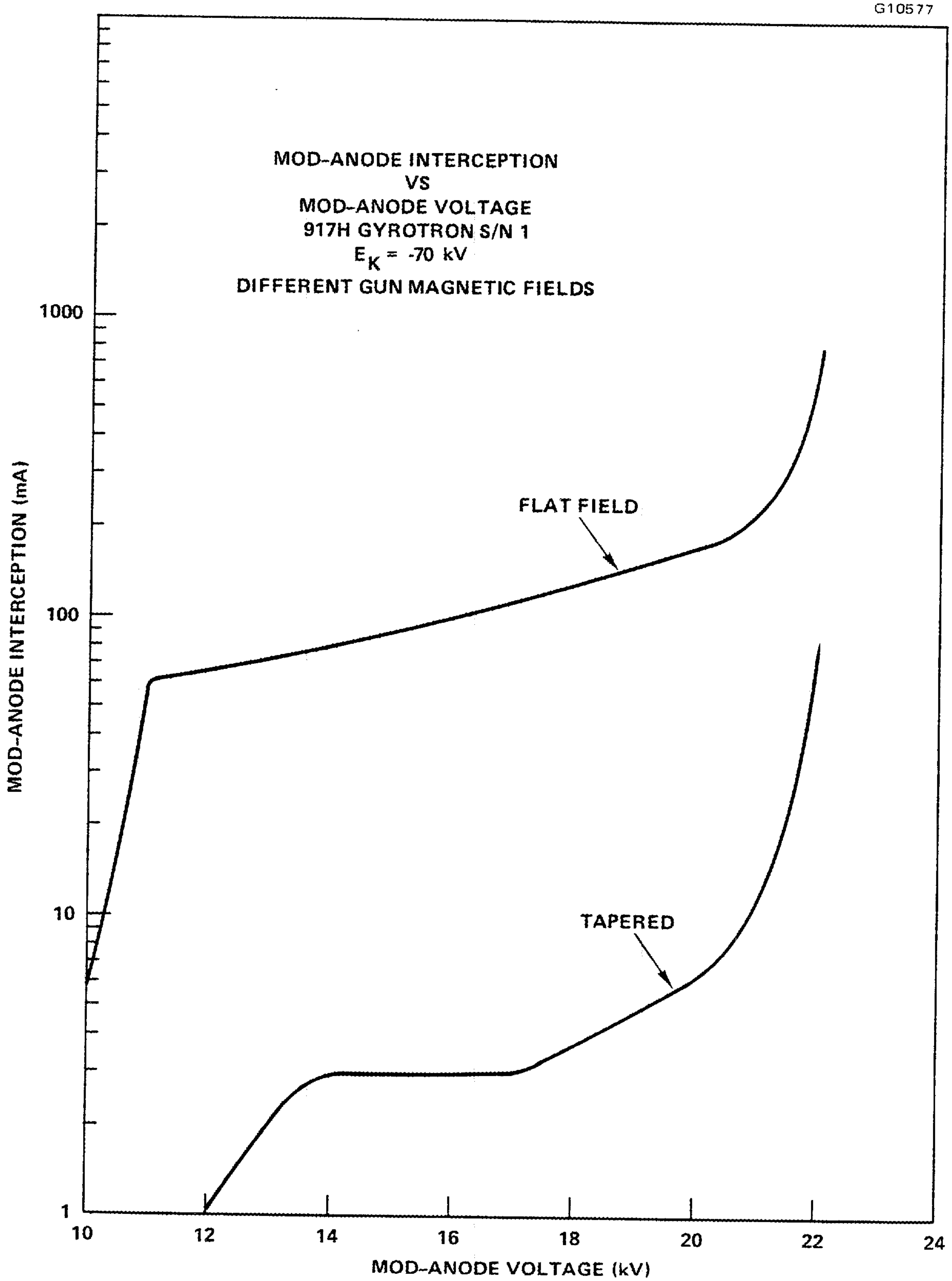

Figure 2-3 Comparison of mod-anode interception for S/N 1 with different gun magnetic fields.

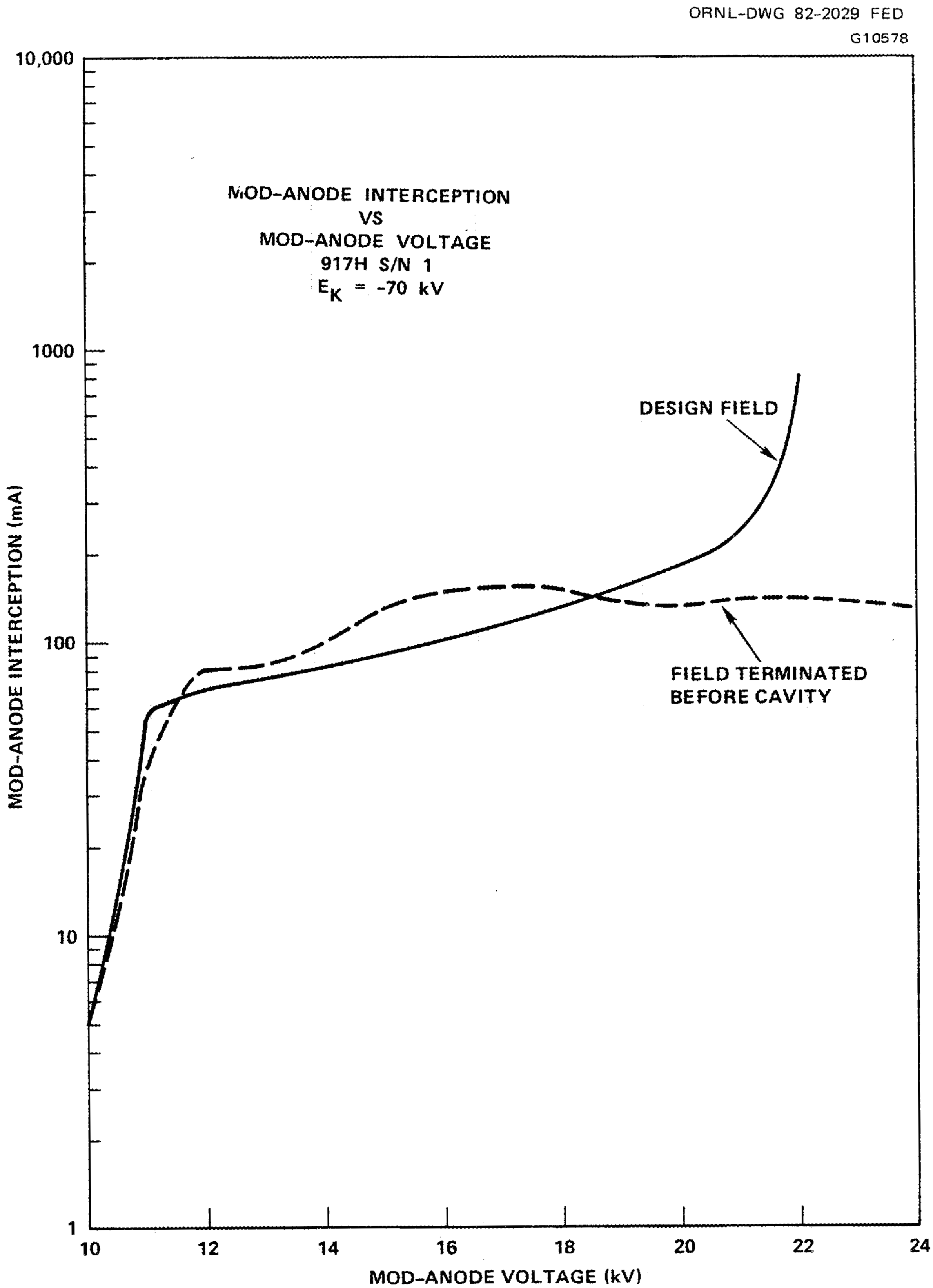

Figure 2-4 Comparison of mod-anode interception in S/N 1 for the "design" magnetic field and where the same field is terminated before the cavity.

Up to 18 kV, interception is approximately the same. Over 18 kV, the continuous magnetic field which allows the beam to pass through the cavity results in higher mod-anode interception. When the magnetic field is terminated in the drift region before the cavity, interception remains relatively constant up to mod-anode voltages of 28 kV. One of two reasons, or possibly both in combination, may account for the sharp rise in mod-anode interception for the case of the continuous magnetic field.

The first possibility is that beam reversal is occurring because too much rotation is being imparted to the beam. Computer prediction of beam reversal for this gun occurs when mod-anode voltage exceeds 23 kV, while Figure 2-4 indicates reversal may be occurring at 18 kV and above. Beam reversal may manifest itself as high mod-anode interception by upsetting the balanced space charge forces in the gun region as the reversed electrons return toward the cathode. This is analogous to high circuit interception in a TWT as too much collector depression is applied. This phenomenon introduces a finite time delay in the gyrotron for electrons to accelerate axially, then decelerate to zero velocity and then reverse course. The calculated round trip transit time between the cathode and cavity is 10 ns with 70 kV applied. However, this delay is considerably shorter than the observed time delays as long as 10 μs previously reported.[1] Therefore, beam reversal because of magnetic mirroring does not in itself explain the high mod-anode interception.

The second possible reason for high mod-anode interception is RF defocusing due to a slow plasma wave traveling within the beam. Such phenomena of beam waves have been widely reported in the literature, and one compilation is given in the references.[3] Without identifying any one specific beam mode, the following conclusions may be drawn to date:

- the frequency of the beam mode is related to the cyclotron frequency in the gun where the magnetic field is homogenous;

- the magnetic tunability of the beam wave is greater than an octave;

- no geometric resonance is apparent in the gun region which would account for this wide tuning range;

- the gun tester, which used an identical gun as S/N 1, did not exhibit unusual mod-anode interception, nor RF emanations;

- the beam wave must therefore be generated in another part of this tube, i.e. the lossy drift section;

- the physical characteristics of the lossy drift section are such that the lowest order mode that could possibly be generated or propagated by the walls is at 9 GHz, whereas frequencies from 2.5 to 5 GHz have been observed.

These conclusions support the concept of a beam space charge instability, propagating along the beam in the drift section, emanating outward from the gun and spoiling the equilibrium of the beam, causing high mod-anode interception. Remaining tests are expected to lend further credence to this hypothesis: cold and hot tests of the lossy drift section. These tests are expected to be completed in the next quarter.

2.3 RF CAVITY

The cavity used in S/N 1 was selected on the basis of ease of oscillation and mode separation. A cavity Q of approximately 700 was used so that the threshold for start oscillation would be conservatively low for the first oscillator. At the same time, a cavity of normallized length equal to 7.5 was chosen to widely separate the possible interfering modes. A consequence of this choice is that tube efficiency is compromised, which was an acceptable tradeoff for the first tube. Output power in the TE_{02} mode was relatively stable and tube oscillations were sustained at beam currents as low as 1.0 Amp.

Deliberate detuning of the magnetic field was implemented in order to search out other modes. These results were previously reported[1] and are rationalized herein. Modes with high longitudinal index were found, and these are attributable to the unusually long cavity chosen. The amplitudes of the non-symmetric modes, however, were unexpectedly high in comparison to TE_{02} output. The high efficiency of modes with large azimuthal index leads to the belief that the beam may have been off center, lending further credence to the tube's poor magnetic alignment. The displaced beam may have been more optimum for non-symmetric modes than for the TE_{02}. Planned magnetic field measurements of the solenoid should verify this conclusion.

A cavity design which will provide more optimum performance has been considered. Several designs with theoretical Q's of 280 to 400 have been evolved. Figure 2-5 is a scaled computer plot of the generic cavities for the next tube interation. Three versions of this type of cavity have been ordered. Cold tests will determine a final choice for use in the next gyrotron.

2.4 MEDIUM PULSE POWER SUPPLY

Testing to date has been conducted with a short pulse power supply having a 20 μs pulse width capability. This supply has been adequate for diagnostic results of tube performance. A supply with 100 ms pulse capability has recently been assembled and is presently being electrically evaluated. This supply has reached a 75 kV, 10A power level, operated into a wet load. The voltage of the modulator switch tube is slightly greater than this applied voltage, and some breakdown to ground has been noted. This problem must be resolved in order to apply voltages as high as 80 kV to the gyrotron.

Effort is continuing on the modulator check-out.

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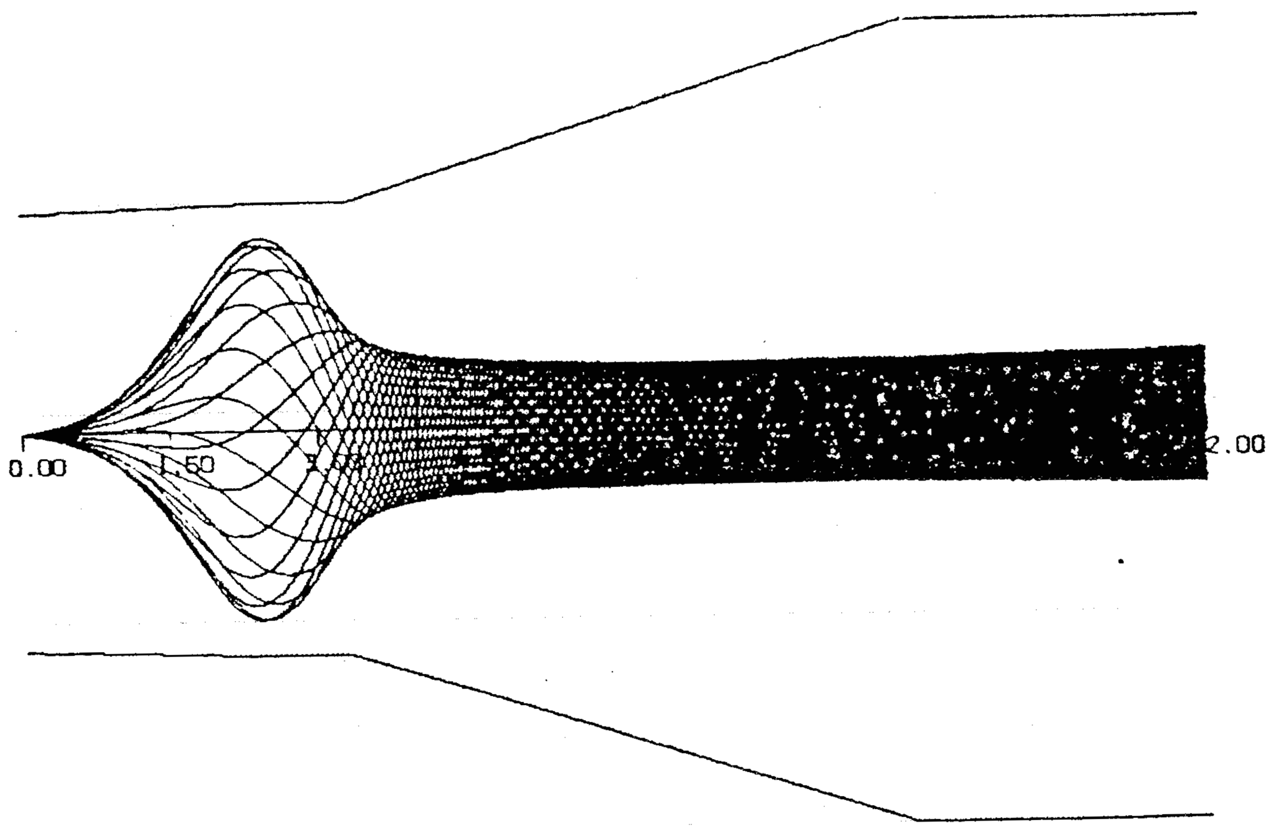


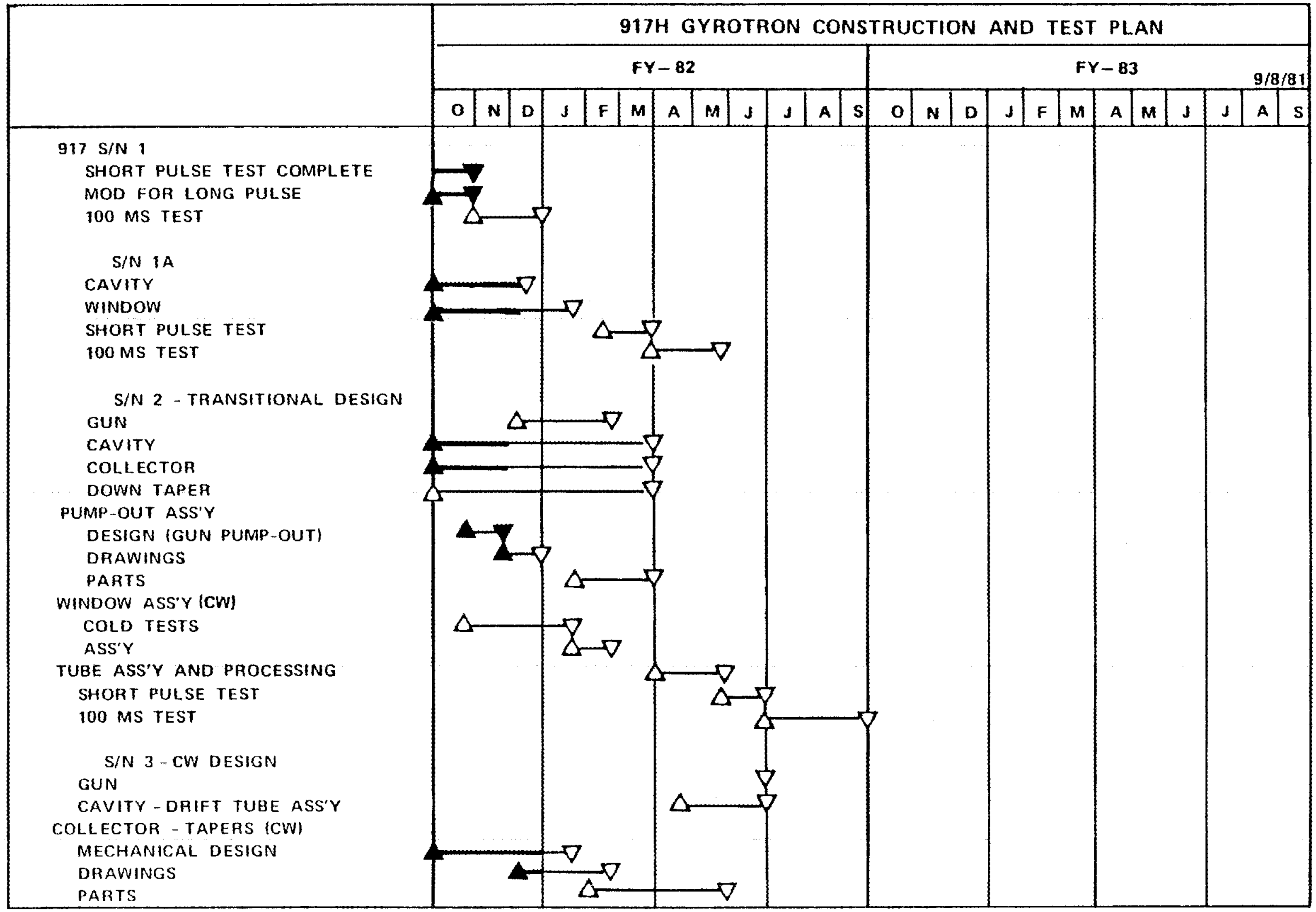
CAVITYQ= 284.532
FREQ(GHZ)=60.02616
Q/QMIN= 0.525
LMODE= 1.442
KLOSS= 6234.7

Figure 2-5 Typical revised cavity design.

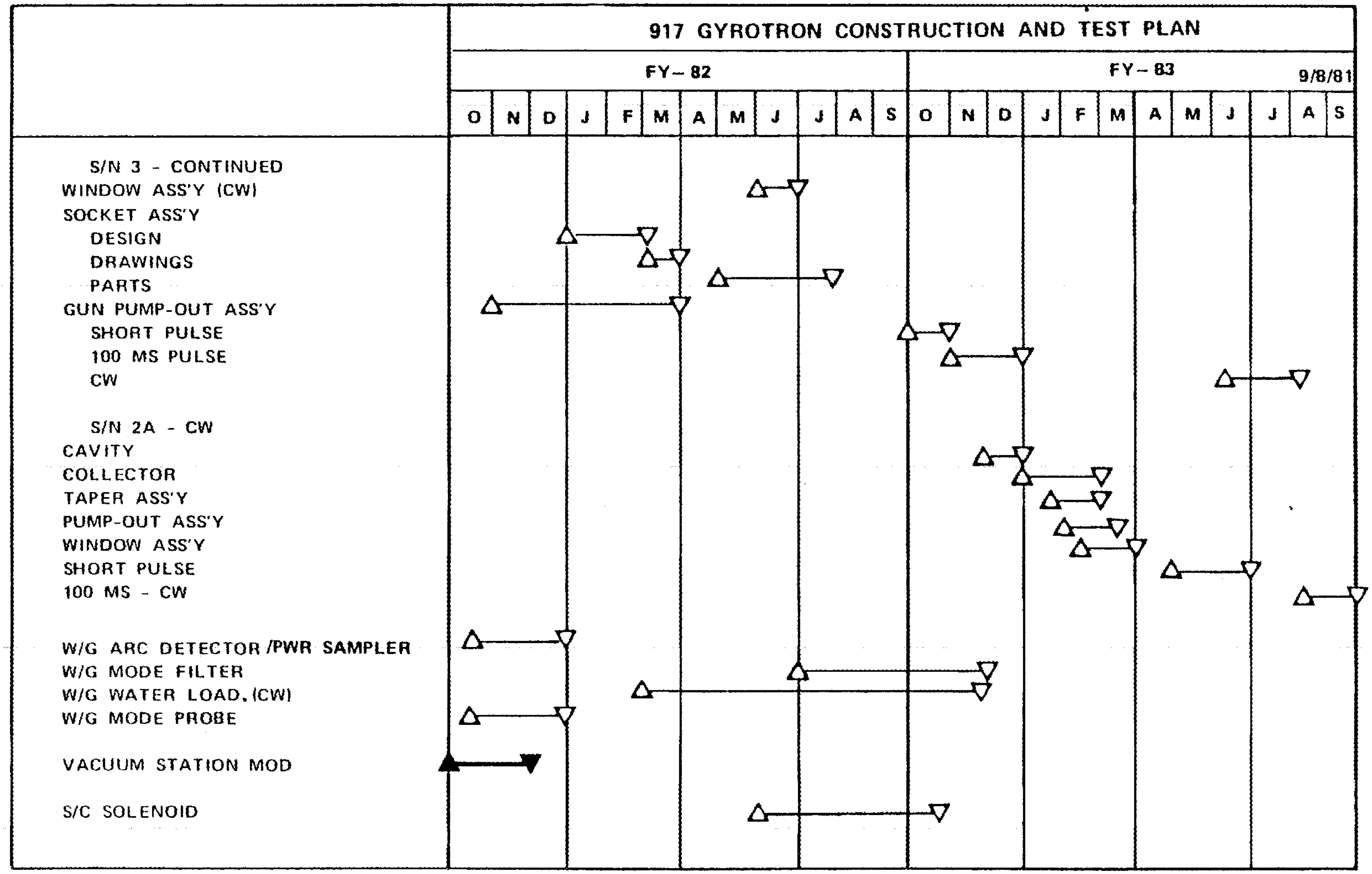
3.0 SCHEDULE

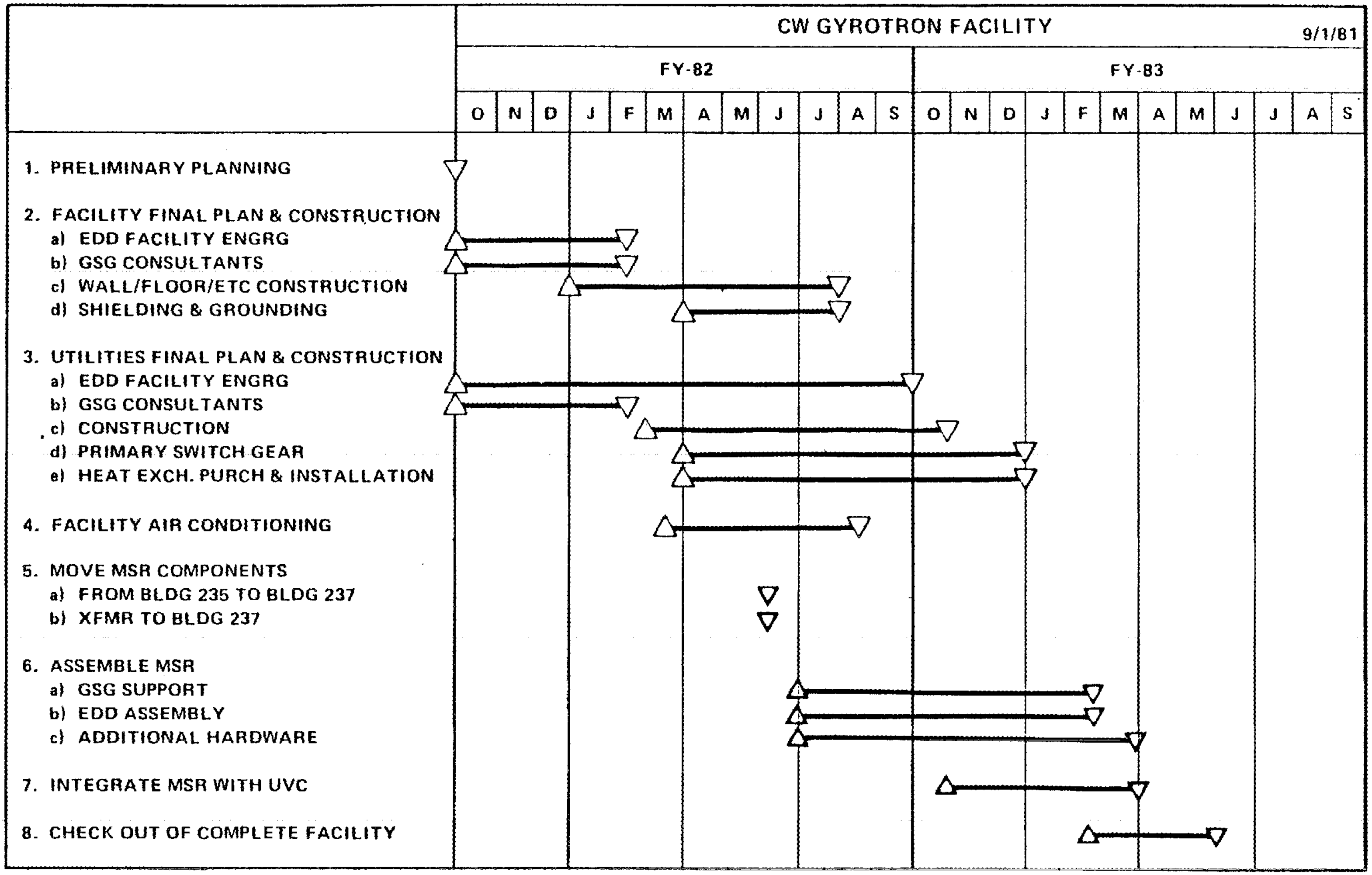
3.1 PROGRAM SCHEDULE

The program schedule as proposed for FY-82 and 83 is shown on the attached milestone charts.



917H GYROTRON CONSTRUCTION AND TEST PLAN
FY – 82
FY – 83
9/8/81
O N D J F M A M J J A S O N D J F M A M J J A S
917 S/N 1
SHORT PULSE TEST COMPLETE
MOD FOR LONG PULSE
100 MS TEST
S/N 1A
CAVITY
WINDOW
SHORT PULSE TEST
100 MS TEST
S/N 2 - TRANSITIONAL DESIGN
GUN
CAVITY
COLLECTOR
DOWN TAPER
PUMP-OUT ASS'Y
DESIGN (GUN PUMP-OUT)
DRAWINGS
PARTS
WINDOW ASS'Y (CW)
COLD TESTS
ASS'Y
TUBE ASS'Y AND PROCESSING
SHORT PULSE TEST
100 MS TEST
S/N 3 - CW DESIGN
GUN
CAVITY - DRIFT TUBE ASS'Y
COLLECTOR - TAPERS (CW)
MECHANICAL DESIGN
DRAWINGS
PARTS


917 GYROTRON CONSTRUCTION AND TEST PLAN
FY– 82
FY– 83
9/8/81
O N D J F M A M J J A S O N D J F M A M J J A S
S/N 3 - CONTINUED
WINDOW ASS'Y (CW)
SOCKET ASS'Y
DESIGN
DRAWINGS
PARTS
GUN PUMP-OUT ASS'Y
SHORT PULSE
100 MS PULSE
CW
S/N 2A - CW
CAVITY
COLLECTOR
TAPER ASS'Y
PUMP-OUT ASS'Y
WINDOW ASS'Y
SHORT PULSE
100 MS - CW
W/G ARC DETECTOR /PWR SAMPLER
W/G MODE FILTER
W/G WATER LOAD, (CW)
W/G MODE PROBE
VACUUM STATION MOD
S/C SOLENOID


CW GYROTRON FACILITY
9/1/81
FY-82
FY-83
O N D J F M A M J J A S
O N D J F M A M J J A S
1. PRELIMINARY PLANNING
2. FACILITY FINAL PLAN & CONSTRUCTION
a) EDD FACILITY ENGRG
b) GSG CONSULTANTS
c) WALL/FLOOR/ETC CONSTRUCTION
d) SHIELDING & GROUNDING
3. UTILITIES FINAL PLAN & CONSTRUCTION
a) EDD FACILITY ENGRG
b) GSG CONSULTANTS
c) CONSTRUCTION
d) PRIMARY SWITCH GEAR
e) HEAT EXCH. PURCH & INSTALLATION
4. FACILITY AIR CONDITIONING
5. MOVE MSR COMPONENTS
a) FROM BLDG 235 TO BLDG 237
b) XFMR TO BLDG 237
6. ASSEMBLE MSR
a) GSG SUPPORT
b) EDD ASSEMBLY
c) ADDITIONAL HARDWARE
7. INTEGRATE MSR WITH UVC
8. CHECK OUT OF COMPLETE FACILITY

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2. Tancredi, J.J., et al, ibid, Quarterly Report No. 8, ORNL/Sub-79/33200/8, April through June 1981.

3. Krall, N.A. and Trivelpiece, A.W., Principles of Plasma Physics, McGraw-Hill Book Co., New York, 1973.

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