ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

THEORETICAL STUDY, DESIGN, AND CONSTRUCTION OF C-W MAGNETRONS FOR FREQUENCY MODULATION

QUARTERLY PROGRESS REPORT NO. 3

Period Covering June 1, 1951, to September 1, 1951
Electron Tube Laboratory
Department of Electrical Engineering

BY

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PERSONNEL

Scientific and Engineering Personnel		Time Worked in Man Months*
W. G. Dow	Professor of Electrical Engineering	Supervisor
H. W. Welch, Jr.	Research Physicist	.09
J. R. Black	Research Engineers	1.25
G. Hok		.23
J. S. Needle	Instructors of Electrical Engineering	1.76
J. A. Boyd		.56
S. Ruthberg	Research Associates	2.04
G. Brewer		.58
W. W. Peterson	Student Assistant	1.18
Service Personnel		
V. R. Burris	Machine Shop Foreman	.05
R. F. Steiner	Assembly Technicians	2.04
J. W. VanNatter		2.89
R. J. Hansen	Technicians	.49
C. A. Jaycox		.23
R. F. Denning	Laboratory Machinists	.72
T. G. Keith		1.76
E. A. Kayser		.42
N. Navarre	Draftsman	2.26
J. Long	Stenographers	.19
A. Kline		.16
E. Brewer		.58
S. Spiegelman		.14
M. Gotanda		1.60

* Time worked is figured on the basis of 172 hours per month.

MAJOR REPORTS ISSUED TO DATE

Contract No. W-36-039 sc-32245. Subject: Theoretical Study, Design and Construction of C-W Magnetrons for Frequency Modulation.

Technical Report No. 1

H. W. Welch, Jr., "Space-Charge Effects and Frequency Characteristics of C-W Magnetrons Relative to the Problem of Frequency Modulation," November 15, 1948.

Technical Report No. 2

H. W. Welch, Jr., G. R. Brewer, "Operation of Interdigital Magnetrons in the Zero-Order Mode," May 23, 1949.

Technical Report No. 3

H. W. Welch, Jr., J. R. Black, G. R. Brewer, G. Hok, "Final Report," May 27, 1949.

Contract No. W-36-039 sc-35561. Subject: Theoretical Study, Design and Construction of C-W Magnetrons for Frequency Modulation.

Technical Report No. 4

H. W. Welch, Jr., "Effects of Space Charge on Frequency Characteristics of Magnetrons," Proc. I.R.E., **38**, 1434-1449, December 1950.

Technical Report No. 5

H. W. Welch, Jr., S. Ruthberg, H. W. Batten, W. Peterson, "Analysis of Dynamic Characteristics of the Magnetron Space Charge, Preliminary Results," January 1951.

Technical Report No. 6

J. S. Needle, G. Hok, "A New Single-Cavity Resonator for a Multianode Magnetron," January 8, 1951.

Technical Report No. 7

J. R. Black, H. W. Welch, Jr., G. R. Brewer, J. S. Needle, W. Peterson, "Theoretical Study, Design, and Construction of C-W Magnetrons for Frequency Modulation," Final Report, February 1951.

Contract No. DA-36-039 sc-5423. Subject: Theoretical Study, Design and Construction of C-W Magnetrons for Frequency Modulation.

Technical Report No. 8

G. R. Brewer, "The Propagation of Electromagnetic Waves in a Magnetron-Type Space Charge," July 1951.

Technical Report No. 10

G. Hok, "Space-Charge Equilibrium in a Magnetron: A Statistical Approach," July 13, 1951.

Technical Report No. 11

J. S. Needle, "The Insertion Magnetron: A New External-Cavity Magnetron for Low-Power Electronically-Tunable Operation in the 10 to 20-cm Wavelength Range," August 1951.

ABSTRACT

This report summarizes the progress made at the University of Michigan Electron Tube Laboratory during the period of June 1, 1951, to September 1, 1951, on Contract No. DA-36-039 sc-5423.

Technical Reports

The major time was devoted to publishing three technical reports entitled:

1. Technical Report No. 8
G. R. Brewer, "The Propagation of Electromagnetic Waves in a Magnetron-Type Space Charge," July 1951.

2. Technical Report No. 10
G. Hok, "Space-Charge Equilibrium in a Magnetron: A Statistical Approach," July 1951.

3. Technical Report No. 11
Jules S. Needle, "The Insertion Magnetron: A New External-Cavity Magnetron for Low-Power Electronically-Tunable Operation in the 10 to 20-cm Wavelength Range," August 1951.

Abstracts of the above reports will appear in the text of this report.

Model 9 Insertion Magnetron

Two new tubes of the Model 9 voltage-tunable series were built and tested. Effort is being made to increase the frequency and power output as well as to reduce the noise of this structure.

Model 8 Rectangular Tube

One tube of the Model 8 series was constructed and tested during this period. This is the high power version containing two sets of oscillator anodes. A parasitic mode of oscillation prevented operation in the desired cavity mode. A tunable version of the Model 8 structure has been designed and is on the pumps.

Models 6 and 7

The experimental work on the Model 6 and 7 structures is being brought to an end in order to devote more effort to the voltage-tunable tubes. To facilitate a renewal of this study at some future date final data of these tubes concerning their erratic behavior are presented. This work will be shelved within the very near future.

Model 13 Interdigital Voltage-Tunable Tube

Investigations are being made with a Sylvania 3J22 external-cavity interdigital tube operating directly into a matched waveguide. Voltage tuning was obtained at low power from 5.78 cm to 13.85-cm wavelength. As a result of this study a tube is being designed to operate into a waveguide structure and is expected to produce approximately 5 watts of voltage-tuned power. This structure will be designated as Model 13.

Trajectron

Weak stray magnetic fields have prevented alignment of the exploring electron beam of the trajectron. Preliminary data are presented concerning the diode section of the trajectron in which negative resistance phenomena are observed.

Theoretical Analysis of Frequency Pushing and Voltage Tuning

The analysis of frequency pushing and voltage tuning is nearing completion. A technical report on this subject will be published within the next two months.

QUARTERLY PROGRESS REPORT NO. 3

THEORETICAL STUDY, DESIGN, AND CONSTRUCTION OF C-W MAGNETRONS FOR FREQUENCY MODULATION

1. Purpose (J. R. Black)

The purpose of this report is to summarize the progress in the University of Michigan Electron Tube Laboratory during the period from June 1, 1951, to September 1, 1951, on Contract No. DA-36-039 sc-5423.

The general objectives of the program under this contract are to increase the knowledge of space-charge effects and frequency characteristics in c-w magnetrons and to apply this knowledge to the development of magnetrons which can be frequency-modulated. Prior to December 1, 1950, the major emphasis has been on the development of an improved understanding of the magnetron space charge and its effects on magnetron modulation and operation. In particular, the magnetron space charge as a reactive element was given rather extensive attention, and more recently the phenomena of voltage tuning and frequency pushing were studied. Several tube structures were developed as a result of these studies, however until recently this development has suffered due to the emphasis on the theoretical approach.

On June 1 there were two primary objectives for the period covered by this report. One was to complete as soon as possible the theoretical aspects of this program and to publish these results in technical reports. The other objective was to emphasize the development of various tube designs under investigation into practical usable forms. The voltage-tunable tubes were to receive the major attention.

In order to devote more effort to voltage-tunable tubes the analysis of data on Models 6 and 7 (coaxial high power f-m and non-f-m structures) was to be brought to a point where work on them could be dropped but easily resumed at some future date.

Work was to continue on the development of the Model 8 series of tubes (rectangular) since this series seems to be most promising for the development of a 500-watt f-m magnetron. Also, a further development of this structure would form a voltage-tunable device at high power levels.

The trajectron was to continue to receive a very small attention (less than 1/3 man month of engineering time per month). This effort is still being continued for it is strongly felt that this experiment will greatly further the understanding of magnetron behavior.

2. Technical Reports (J. R. Black)

Three technical reports were published in the period covered by this progress report. A fourth technical report consisting of translations from the French of four papers presented by Doehler et. al. is nearly complete, but the printing is to be delayed until early December.

The following is a list of the technical reports with their abstracts which were published during this period.

1. Technical Report No. 8

   G. R. Brewer, "The Propagation of Electromagnetic Waves in a Magnetron-Type Space Charge," July 1951.

   Abstract: The propagation of electromagnetic waves in a magnetron-type space charge is studied by using small signal, non-relativistic approximations. The following cases are analyzed:
   1. Plane Magnetron
      a. Propagation of a plane electromagnetic wave in a direction parallel to the applied magnetic field.

  - b. Propagation of a plane electromagnetic wave in a direction perpendicular to the applied magnetic field and normal to the anode and cathode.
  - c. Propagation of a plane electromagnetic wave of phase velocity slow compared to that of light in a direction perpendicular to the applied magnetic field and parallel to the electron drift motion.

2. Cylindrical Magnetron
   - a. Propagation of a TEM-type electromagnetic wave in a cylindrical space charge in a direction parallel to an axially applied magnetic field.
   - b. Radial propagation of a cylindrical electromagnetic wave in a cylindrical space charge.

The analysis yields values for the propagation constant of the wave in the space charge, expressed in terms of an effective dielectric constant, which depends on the ratio of the signal radian frequency ω to the cyclotron radian frequency ω_c ($= eB_0/m$). It is found that this effective dielectric constant can assume any real value, positive or negative. For given ω/ω_c, this knowledge of the effective dielectric constant makes possible the determination of the reactive effects of the space charge on a confining circuit.

The influence of the space charge on the frequency of a multianode magnetron is discussed qualitatively, as is the possibility of amplification of an electromagnetic wave along the plane magnetron space charge. Several experiments, conducted to determine the validity of the theory, are described. The results of these experiments appear to confirm certain critical parts of the theory.

2. Technical Report No. 10

G. Hok, "Space-Charge Equilibrium in a Magnetron: A Statistical Approach," July 1951.

Abstract: This report discusses the steady-state space-charge distribution in a d-c magnetron when its anode voltage is lower than its cutoff voltage. It is shown that the discrete electron-to-electron interaction has a cumulative effect on the space-charge distribution that is not negligible. The distributions derived by Brillouin, Slater, and others are not steady-state distributions, since they are obtained without regard to the discrete interaction. The actual distribution and its dependence on the ratio of anode voltage to cutoff voltage are discussed qualitatively, but no attempt is made to calculate the space-charge distribution explicitly.

3. Technical Report No. 11

Jules S. Needle, "The Insertion Magnetron; A New External-Cavity Magnetron for Low-Power Electronically-Tunable Operation in the 10 to 20-cm Wavelength Range," August 1951.

Abstract: In this report we consider the design, construction, and performance of a new type of low-power, external-cavity, multianode magnetron for operation in the 10 to 20-cm wavelength range. Special attention is given to the problem of wide-range tunability using either mechanical or electrical methods.

The basic structure of this new magnetron consists of a short hermetically-sealed section of coaxial transmission line which can be used with an external cavity. The sealed-off section contains a multianode structure consisting of six equally-spaced radial vanes extending from the inner wall of the outer coaxial cylinder into six longitudinal slots in the inner coaxial cylinder. The cathode is symmetrically located within the inner coaxial cylinder at the position of the multianode structure. This sealed-off structure is used to excite a TEM mode in an external coaxial circuit.

Design equations for a mechanically-tunable coaxial-line resonator are derived and are utilized in the design and construction of a prototype resonator.

Experimental observations of mechanical and electronic tunability are reported for a number of tubes with particular emphasis on the electronic or voltage-tuning aspects. These experimental observations are interpreted in terms of computed circuit properties.

3. Model 9 Low-Power Insertion Magnetron (J. S. Needle)

In addition to the completion of Technical Report No. 11,* two new tubes were completed during this period.

Model 9D No. 60 was tipped off the pumps and given a preliminary oscillation test. This tube uses an oxide-coated cathode and an anode structure consisting of six bars and three equally-spaced vanes instead of six vanes. The change in the number of vane anodes was made in order to reduce the lumped capacitance of the anode structure thereby allowing higher frequency operation. The preliminary tests on this structure in a tunable coaxial cavity were disappointing since the frequency of oscillation was found to be independent of the length of the coaxial cavity. The tube is evidently operating in a "vane mode" under these conditions. Further tests will be conducted with this structure in an external low-Q circuit in order to investigate voltage-tunable properties.

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* J. S. Needle, "The Insertion Magnetron: A New External-Cavity Magnetron for Low-Power Electronically-Tunable Operation in the 10 to 20-cm Wavelength Range," Technical Report No. 11, Electron Tube Laboratory, University of Michigan, Ann Arbor, August 1951.

Model 9B No. 58 was tipped off the pumps and tested under pulsed operating condition in a low-Q external circuit. This tube contains a throiated tungsten helical cathode. Pole pieces were incorporated on the cathode stem in order to attain a more uniform magnetic field in the interaction space. Voltage-tunable operation was obtained with this structure but comparisons with other tubes as to noise properties have not been made as yet.

An investigation of different circuit geometry for the Model 9 structure was started during this period. This geometry has been adopted from the type 805 Hewlett Packard parallel-plate slotted line.* A prototype parallel-plate line of this type has been completed and initial tests indicate satisfactory performance. One of the advantages of the parallel-plate structure over that of the coaxial line structure is the greater ease of mechanical tuning.

Further investigations on the insertion tube will continue with emphasis on noise reduction and external circuitry. A study of the literature on magnetron excess noise has already begun and some noise measurement equipment has been procured.

4. Model 8 Double-Anode Set Interdigital Magnetron (J. R. Black)

The Model 8 structure is essentially a rectangular cavity, electrically one wavelength long, loaded at each of the two voltage maxima by a set of interdigital anodes. Such a structure having two cathodes and two sets of anodes would form a high-power c-w magnetron. If one of the anode sets is replaced by a mechanically-tunable variable condenser, the

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* W. B. Wholey and W. N. Eldred, "A New Type of Slotted Line Section," Proc. I.R.E., 38, 3, March 1950.

structure will form a mechanically-tunable magnetron. Furthermore, if one of the anode sets is replaced by an anode set which is designed to form a variable reactance tube using a magnetron-type space charge, the structure would form an f-m tube.

The Model 8 structure was originally conceived as an f-m tube, but to date the effort has been placed on the development of a high-power double-anode tube and lately on a mechanically-tunable tube. It is felt that these structures will lead to results immediately applicable to developing an f-m tube.

The geometry and initial cold tests of the Model 8B high-power magnetron was discussed in the Quarterly Progress Report No. 2, June 1951, pages 14 through 19. A drawing of this tube is given in Fig. 4.1 and a photograph in Fig. 4.2. The above tube was constructed during this period and due to a shifting of jigs during brazing the anodes were not inserted their full depth in the tube. The distance between the ends of the teeth and the bottom of the cavity is .065 in. rather than the desired .035 in. The reduction in anode capacity due to this change in anode depth reduced the λ-mode wavelength from 13.2 to 12.3 cm.

Model 8B operated in two different modes of operation, neither of which was the desired cavity λ mode. They were the cavity 2λ mode at λ = 8.5 cm (f = 3530 mc) and in a parasitic mode of λ = 14.9 cm (f = 2012 mc). The parasitic mode was associated with the coaxial lines formed by the cathodes, the pole pieces and the cathode chokes.

Fig. 4.3 shows three pulsed-performance oscillograms of the Model 8B. The upper curve shows the voltage-current diagram of only the No. 1 cathode, while the center curve is the No. 2 cathode performance diagram. The lower curve of Fig. 4.3 shows the performance diagram of both cathodes operating.

DWG. NO. B

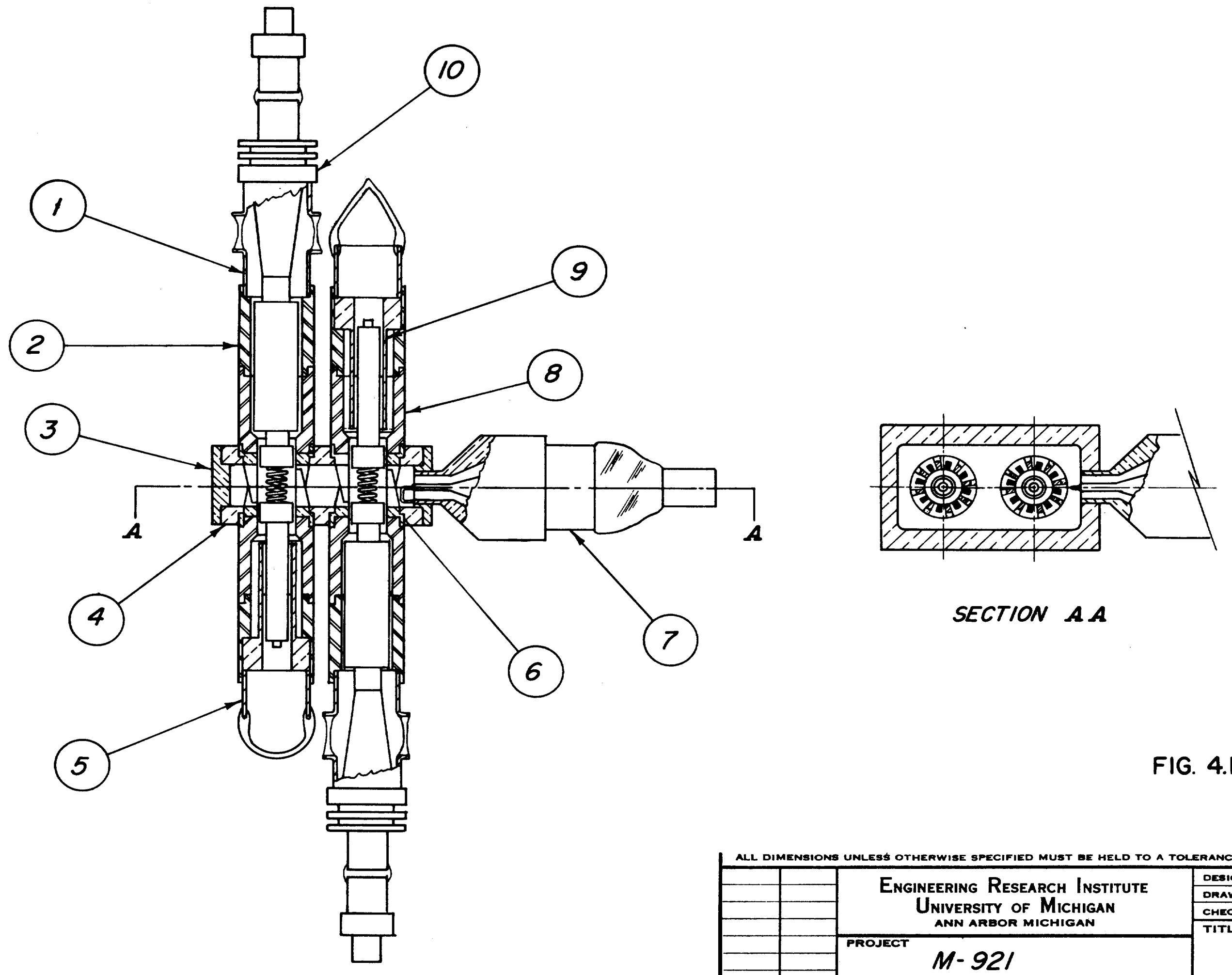

FIG. 4.1

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED MUST BE HELD TO A TOLERANCE - FRACTIONAL ± 1/64," DECIMAL ± .005," ANGULAR ± ½°

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PROJECT M-921

CLASSIFICATION

ISSUE | DATE

DESIGNED BY
DRAWN BY MM
CHECKED BY
APPROVED BY
SCALE FULL
DATE 6-12-51

TITLE PUSH-PULL MAGNETRON
MODEL 8B

DWG. NO. B- 10,008B

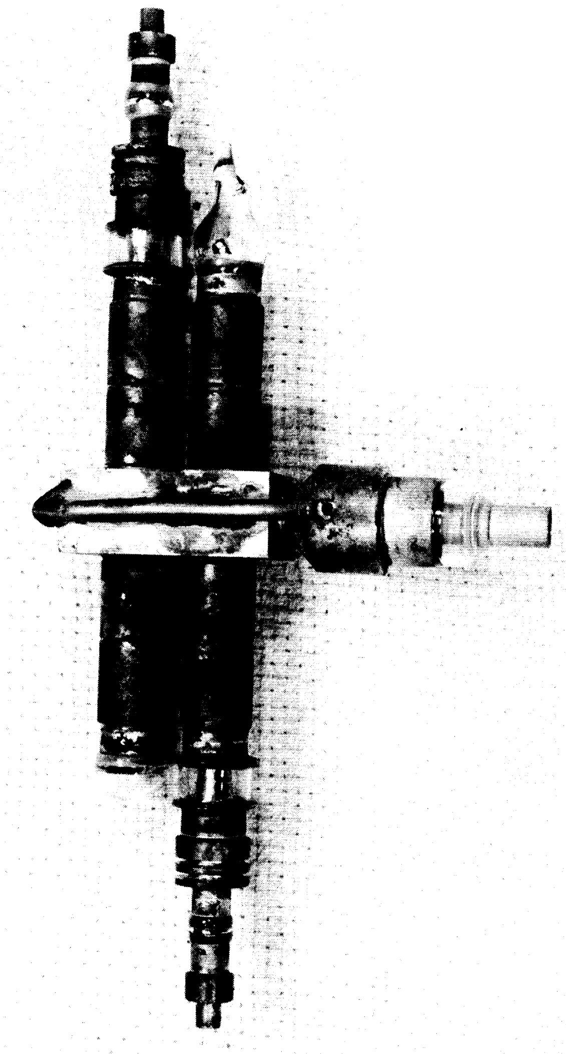


FIG. 4.2
PHOTOGRAPH OF MODEL 8B

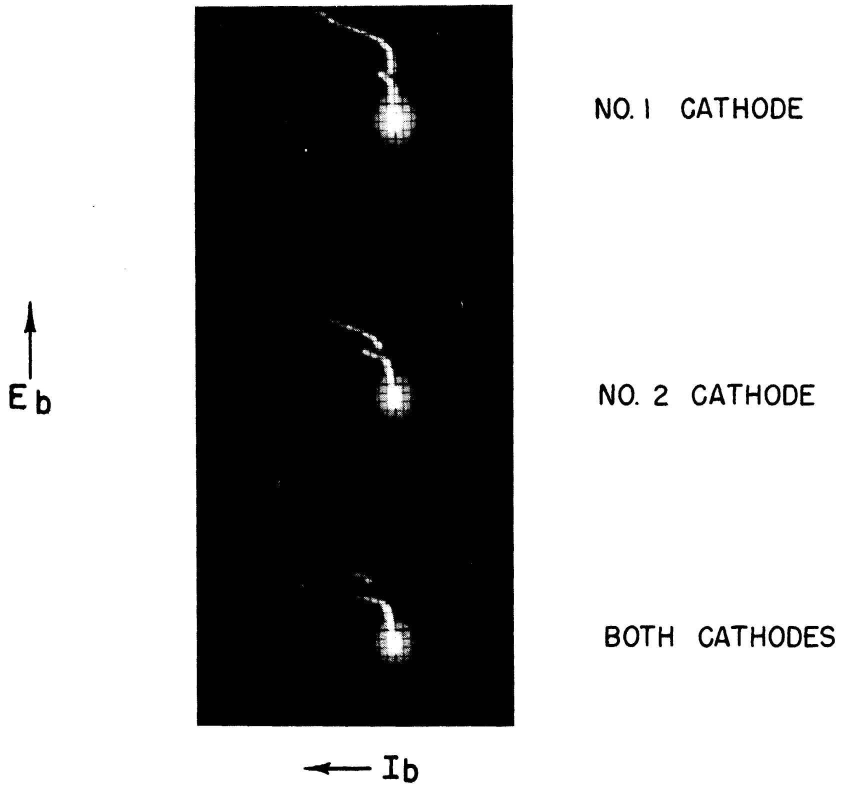


FIG. 4.3
PULSED PERFORMANCE OSCILLOGRAMS MOD. 8B
CURRENT CALIBRATION = 25 MA. PER DIVISION
VOLTAGE CALIBRATION = 330 V. PER DIVISION

It is of interest that the maximum-current boundary for the 14.9-cm wavelength mode with both cathodes operating was considerably greater than the total of the maximum-current boundaries for the cathodes operating individually. With both cathodes operating together the maximum-current boundary is 290 ma, as compared to 155 ma when the cathodes are operated individually. This is a factor of about 1.9 to 1 and indicates that space charge, as far as the mode boundary is concerned, likes to work into a high impedance. Tube failure prevented a further investigation of this phenomenon, however it will be continued in future models.

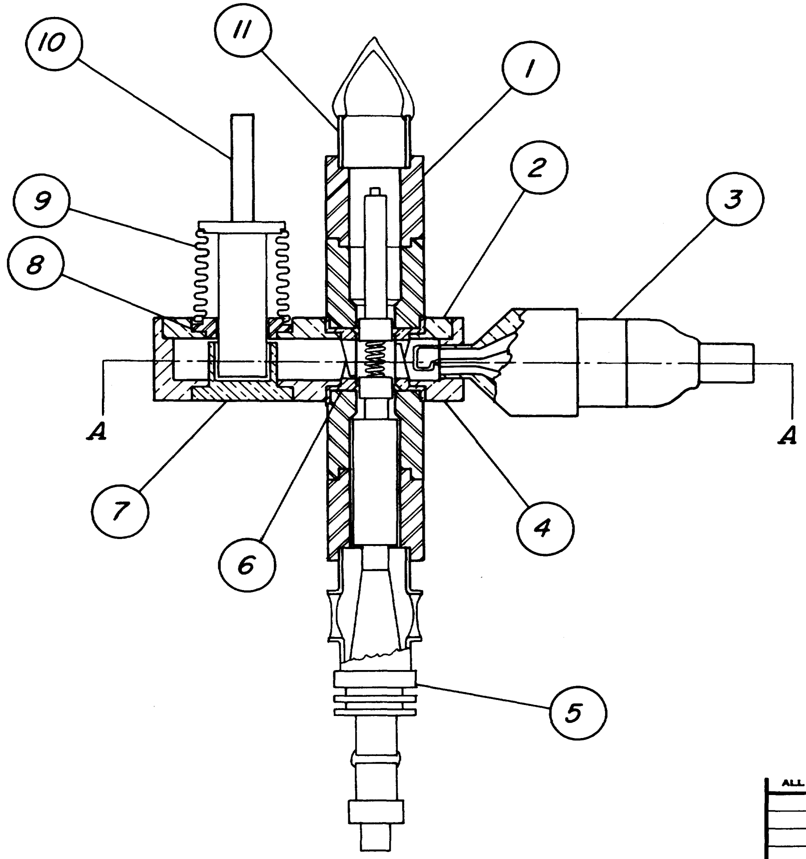
The Model 8B tube is being reconstructed omitting the cathode chokes mounted in the upper cathode line (Part 9 in Fig. 4.1). This change should discourage the appearance of the 14.9-cm mode.

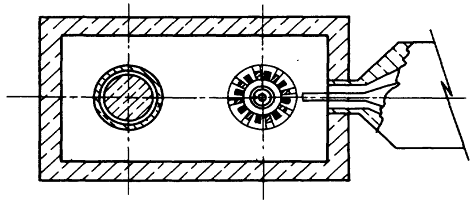
A Model 8C tunable magnetron is at present on the pumps. A drawing of this tube is shown in Fig. 4.4. As shown, a simple cup-rod mechanically variable capacitance is to be used as a tuner. A cold test tuning curve of this structure without the cathode is shown in Fig. 4.5. It should be noted that no spurious resonances were discovered by this test, however the field about the anode became distorted at wavelengths below 15 cm. This is due to the node of the λ mode beginning to intersect the anode structure. It is felt that oscillations should still be supported in this case, however the efficiency may suffer.

The Model 8C tunable tube should provide information leading to a proper cathode design for use with the Model 8B tube.

The cathodes employed in the Model 8 series of tubes are of the carborized thoriated tungsten type providing approximately 4 amperes of emission.

DWG. NO. B





SECTION A.A

FIG. 4.4

ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED MUST BE HELD TO A TOLERANCE - FRACTIONAL ± 1/64," DECIMAL ± .005," ANGULAR ± 1/2°

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CHECKED BY
APPROVED BY
SCALE FULL
DATE 10-5-51

TITLE TUNABLE MAGNETRON MODEL 8C

DWG. NO. B- 10,008C

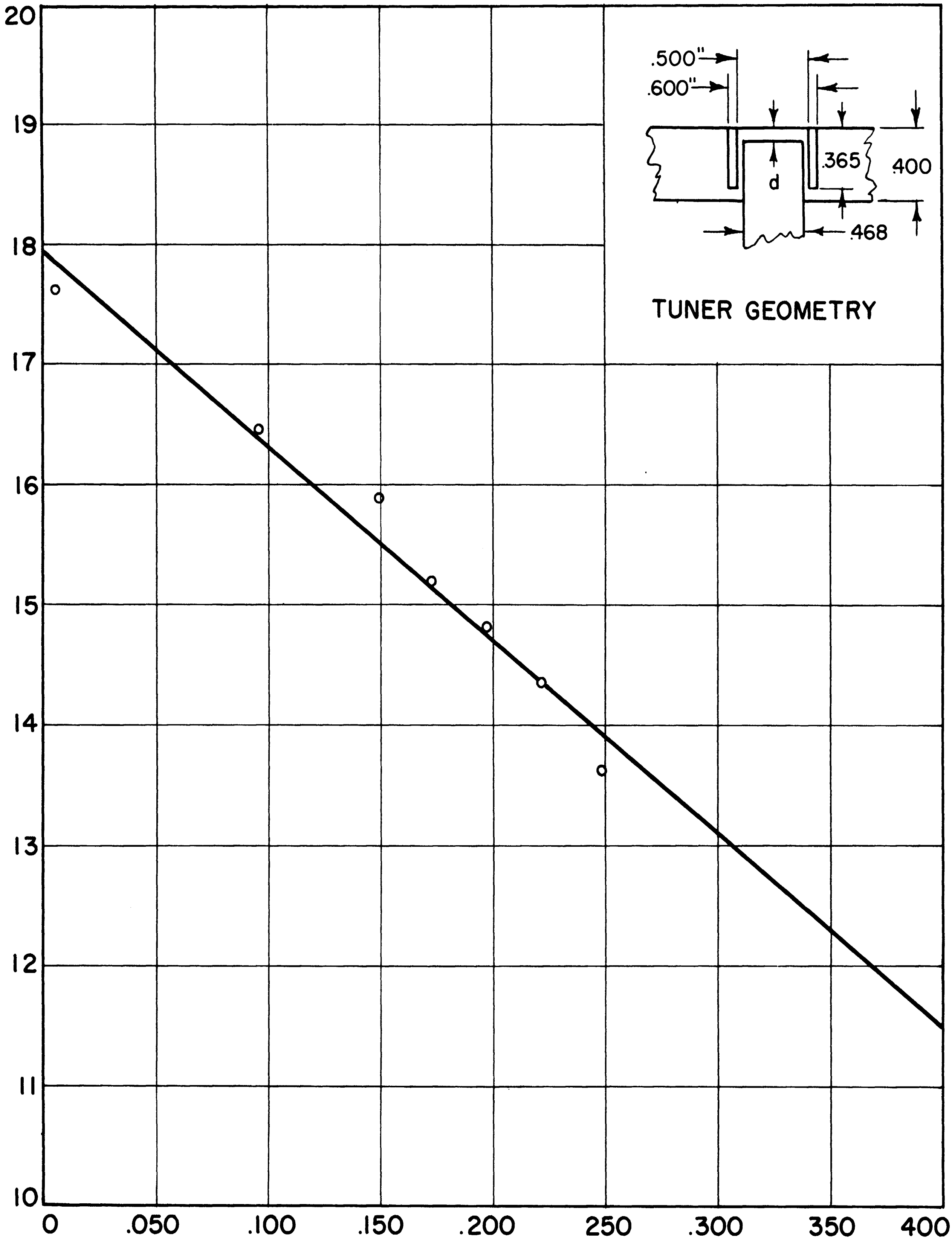

FIG. 4.5
COLD TEST RESONANT WAVELENGTH VS. GAP DISTANCE OF VARIABLE CAPACITANCE

5. Model 6 F-M Magnetron (S. Ruthberg)

The Model 6 f-m magnetron has a coaxial resonant system, two anode sets, and two cathodes. The cavity is electrically one wavelength long for the desired (TEM) mode of operation (λ = 13 cm). Voltage maxima appear at each anode set. The oscillator section consists of 16 anodes, and the modulator section has 4 anodes. (See assembly drawing in Appendix of Technical Report No. 7, February 1951.)

Problems concerning power leakage down the cathode line, mode-jump current, etc., are being investigated using the Model 7 magnetron, which has a less complicated structure, but which is identical to the oscillator section of the Model 6. The Model 7 coaxial cavity resonator is electrically one-half wavelength long and has no provision for frequency modulation.

The objective is to bring the study of this structure to a point where work on it can be stopped but readily resumed at some future date. This decision was made in order to devote more time to voltage-tunable tubes.

A rather extensive study of three different tube structures is being made to determine, if possible, the cause of the erratic behavior of the Model 7. These structures are the Model 7D, with large loop area, the Model 7A, with external line on the cathode structure, and the Model 7F, a mechanically-tuned device. In addition, information on the modes of operation of Model 7E (modified vane structure) is presented.

Assembly drawings of Model 7A and 7B (which is identical with Model 7D except that 7D has twice the coupling loop area) are shown in the Appendix of Technical Report No. 7. Model 7E is identical to Model 7B except the vane structure of Model 7E is modified as shown in Fig. 5.5, page 26, of Quarterly Progress Report No. 2, June 1951. The assembly drawing of Model 7F is shown in Fig. 5.1, page 21, of Quarterly Progress Report No. 2, June 1951.

The erratic behavior of the Model 7E No. 45 magnetron (modified vane structure) was presented in Quarterly Progress Report No. 2, June 1951, page 22, along with two volt-ampere characteristics. The tube exhibited a large number of modes of operation. A study has been made to identify these modes by applying the Hartree equation to experimentally determined starting voltages and wavelengths.

This is done by the following method. If k represents the number of r-f periods necessary for an electron to complete one revolution of the interaction space, its angular velocity is $2\pi f/k$, where f is the frequency of the r-f field. Then, in these terms, the Hartree equation is

$$E = \pi(r_a^2 - r_c^2)\, B \frac{f}{|k|} - 4\pi^2 \frac{m}{e} r_a^2 \frac{f^2}{|k|^2} \qquad 5.1$$

from which the value of $|k|$ may be found. r_a, r_c, B, and f are respectively the anode radius, cathode radius, magnetic field density, and frequency. The quantity k is related to the number of wavelengths of the r-f field in the circumference of the interaction space by

$$k = n \pm p N; \qquad p = 0, 1, 2, \ldots \qquad 5.2$$

where n is the number of waves of the r-f field around the periphery and N is the number of anode segments. n is called the mode number for the interaction space. If $p = 0$, $k = n$, which indicates the electrons move in synchronism with the traveling r-f wave. If $p \neq 0$, the number of r-f periods taken by the electrons to travel around the interaction space differs from the time taken by the r-f wave to cover the same distance. If $p > 0$, the transit time of an electron from gap-to-gap in the anode is p r-f periods greater than that of the r-f wave. If the electrons move from gap-to-gap faster than the r-f wave, they would, on the average, not give energy to the r-f field. $p < 0$ indicates the electrons are moving in the reverse direction to the r-f wave but in such a way as to convert their d-c energy to r-f. So $p \neq 0$ leads to other volt-ampere characteristics than for the case of $k = n$. These cases of $p \neq 0$ are called the Hartree harmonics. The approximate values of k found by use of Eq. 5.1 have been placed on the volt-ampere curves of Fig. 5.1. The interesting range of wavelengths is in the $\lambda = 12.8$-cm region, since this seems to include the main cavity mode. For comparison, the Hartree voltage for a given choice of k is found to be greater than the actual starting voltage and is in agreement with the usual experience of finding the starting voltages less than the Hartree voltages. These facts indicate that $k = 8$ for the mode appearing in the 1300 to 1400-volt range, $k = 9$ in the 1100 to 1300-volt range, and $k = 10$ in the 1100-volt range. Values of k for other volt-ampere characteristics at different magnetic fields agree with those presented.

In the desired cavity mode (TEM) $k = n = N/2 = 8$ for π-mode operation of the anode structure. The first Hartree harmonic would then appear for $p = 1$ at $k = 24$. Apparently, the tube operates in the $n = 8$ mode for the 1300 to 1400 volt characteristic. However, the Hartree harmonics for this mode do not explain the appearance of $k = 9$ or 10, and as yet no convincing argument has been devised to explain them. Preliminary investigation indicates that a TE_{m1} mode in the cavity could produce the $k = 9$ or 10 configuration within the interaction space, but this analysis is complicated by the vane structure. For this mode of operation modal lines in the electric field occur along diameters in the cavity. Such a cavity operation would give rise to pairs of anode potential waves in the interaction space which are the components of a wave of periodicity N/2 or 8 with an envelope

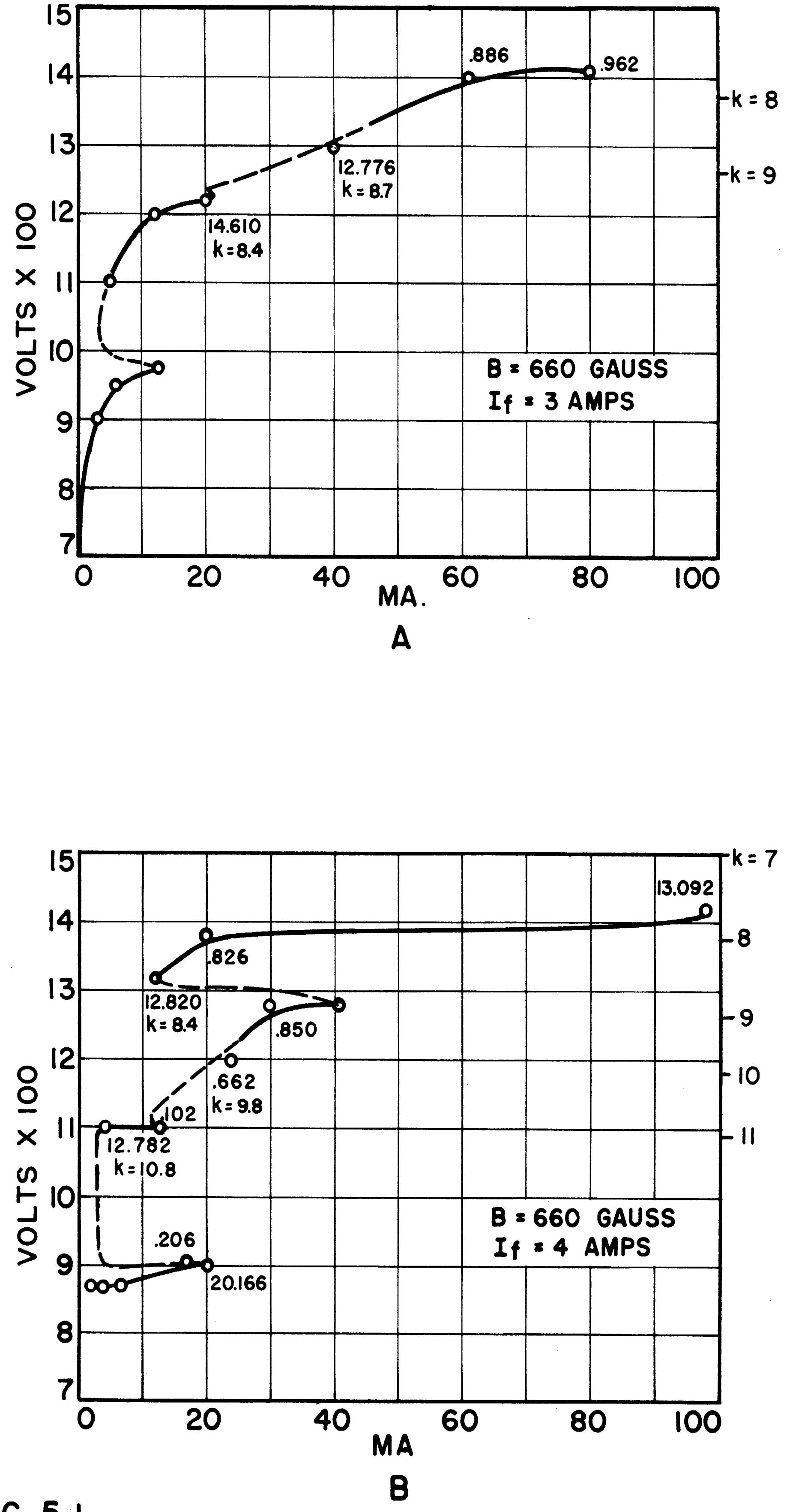

FIG. 5.1

VOLT AMPERE CHARACTERISTICS MODEL 7E 45

whose variation is that of the field in the cavity. Thus, the pairs of waves for

$$n = 8 \pm s \qquad s = 0, 1, 2, \ldots$$

where s is the periodicity of the cavity field. Hartree harmonics can exist for each of these waves. Then $|k| = 9$ might exist as the fundamental $k = n = 9$ or as the first Hartree harmonic of $n = 7$ or $k = 7 - 16$. However, $k = 10$ demands a fundamental of $n = 6$. But one would expect the resonant frequency for these TE modes to be quite different from the TEM; for example, the resonant wavelength for a TE_{11} mode in a cavity of the dimensions of Model 7 would be in the neighborhood of 6 cm when the vane and coupling structures are disregarded.

The performance chart of the Model 7D 42 tube given as Fig. 9.4 in Technical Report No. 6 issued in January 1951 shows large pushing at high magnetic fields. This would be a desirable feature for the oscillator section of the Model 6 f-m tube; consequently, this tube was re-examined in the region of high magnetic fields.

The resultant performance (Fig. 5.2) was found to be radically different from that previously obtained. (See Fig. 9.4, Technical Report No. 6.) The new performance diagram indicated erratic behavior especially in the appearance of frequency doublets. Wavelengths were measured with a coaxial wavemeter whose output fed into a crystal. The doublets were observed as a double maximum in the crystal current. Further examination of such points of operation with a spectrum analyzer showed the output to consist of many frequencies. Furthermore, the wavelengths increased as the mode-jump current was approached, which was quite the opposite in normal operation. This tube failed before more complete data could be obtained.

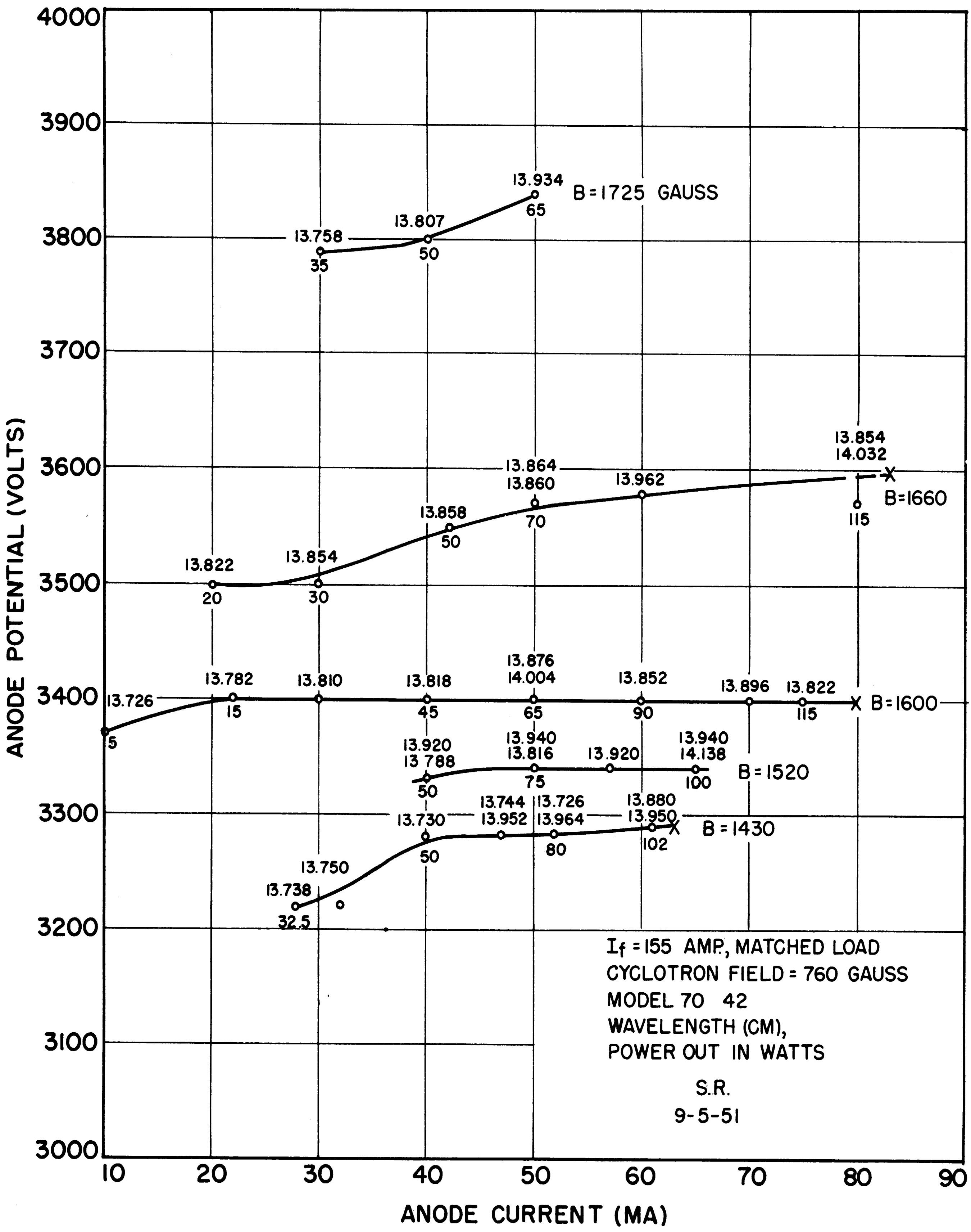

FIG. 5.2

PERFORMANCE CHART FOR COAXIAL SINGLE-CAVITY MAGNETRON

FUNDAMENTAL-CAVITY MODE

Cold tests on the tube showed three resonances in the range of wavelengths from 10 to 15.5 cm. These are seen in the graph of voltage standing-wave ratios vs wavelength, Fig. 5.3. The resonance at $\lambda = 12.96$ cm is an undercoupled case with a loaded Q of about 10. The other two are overcoupled cases. The resonance at $\lambda = 14.6$ cm is given in more detail in Fig. 5.4. Q_L for this mode is about 41. A comparison is made in this figure with the results found previously.

The large discrepancy between the past and present results indicates that some mechanical or electrical change has occurred in the tube itself so that the two sets of information are not comparable. However, due to the unusual behavior of this tube, these results have been incorporated in this report.

In order to study the effects of cathode impedance on tube operation, the Model 7A 33 containing a small diameter cathode (anode-to-cathode ratio = 2.47) and having no choke or bypass on the stem was operated under pulsed conditions with an external coaxial-line stub tuner mounted on the cathode. Without this external tuner the tube operated strongly in the vane mode but weakly in any other mode. The external cathode-line tuner did not cause a large increase in the upper-mode-current boundary although small variations could be observed. Both 14 and 16-cm modes could be made to appear, but the 14-cm mode was intermittent. It is believed that considerably more information could be obtained using this approach by incorporating a tuner which would produce a wider range of impedances at the cathode. The d-c voltage isolation problem associated with this tube makes a wider range of impedance difficult to obtain. The problem will be studied further using a Model 9 tube. When a slotted line was coupled to the cathode in place of a stub tuner, it was noted that power could be coupled out the cathode at the vane-mode wavelength as well as the 14 and 16-cm wavelengths.

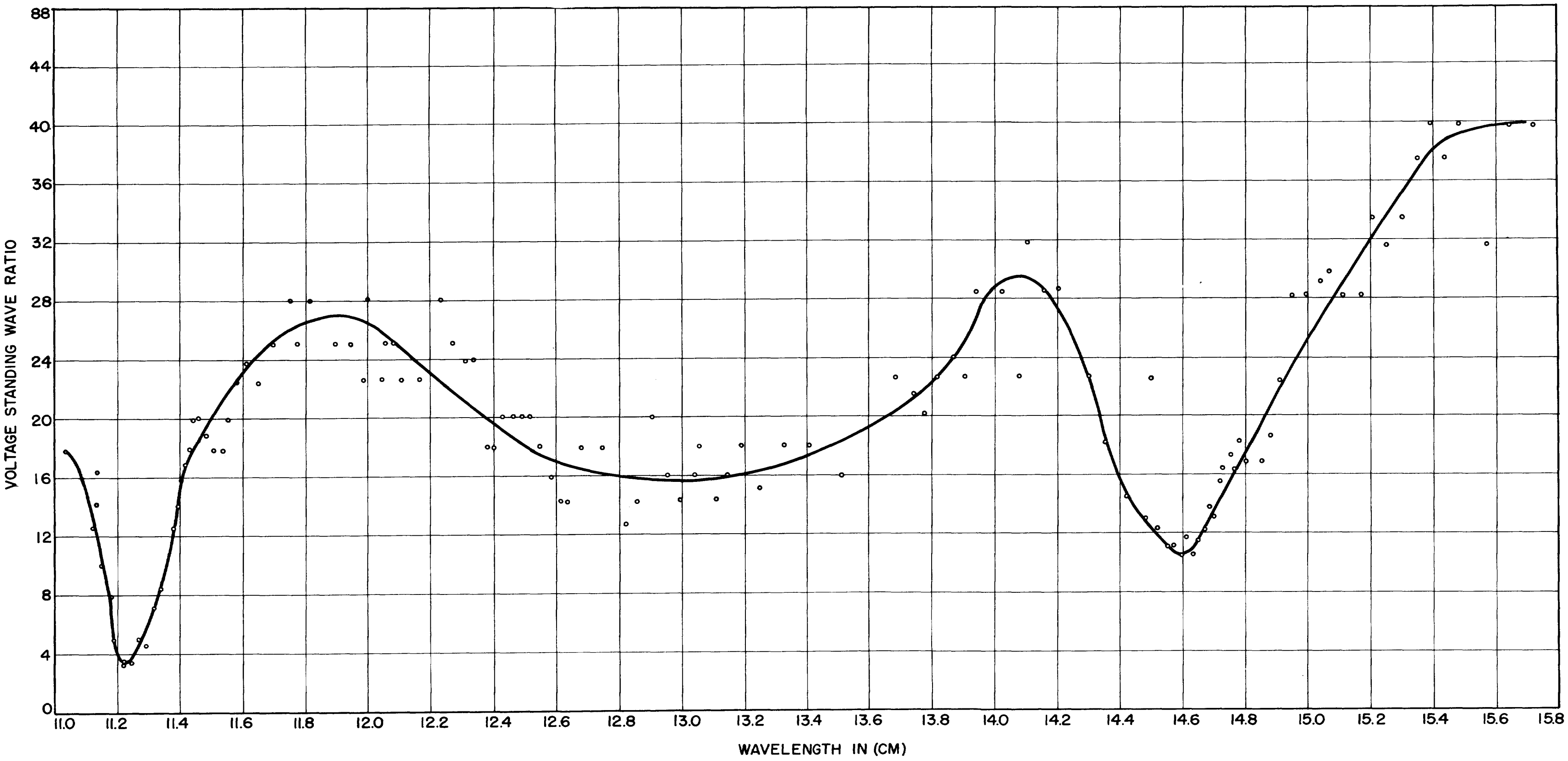

FIG. 5.3 VOLTAGE STANDING WAVE RATIO VS. WAVELENGTH; MODEL 7D NO. 42

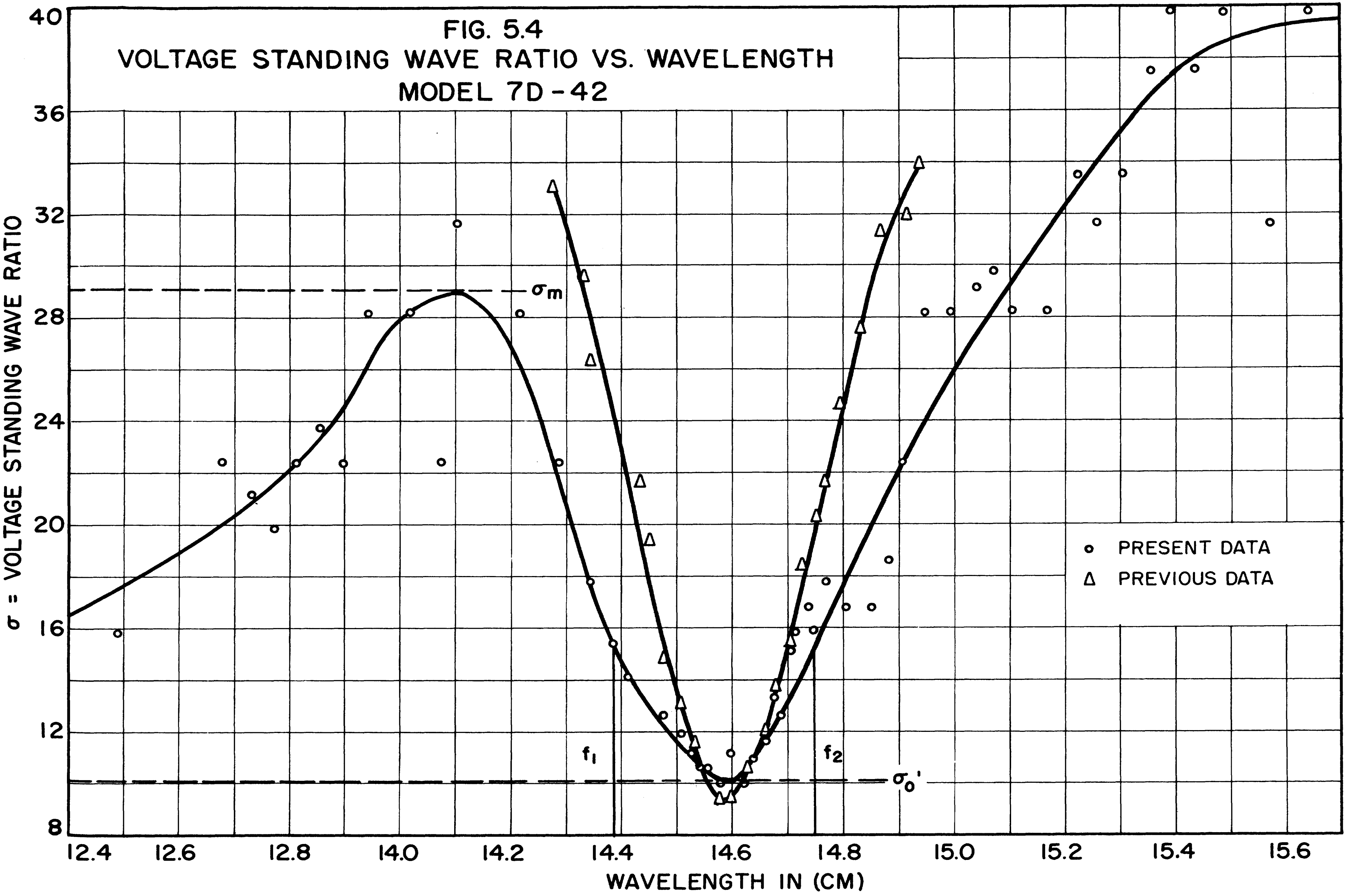

FIG. 5.4
VOLTAGE STANDING WAVE RATIO VS. WAVELENGTH
MODEL 7D-42

The mechanically tunable Model 7F 55 magnetron has been operated over the range of $\lambda = 14.8$ cm to $\lambda = 17.1$ cm. The mode-jump current is extremely low over the entire wavelength range with a maximum of about 15 ma. This tube will be tested further during the next quarter and reported on in greater detail in the final report for this project.

6. Model 13 Low-Power External-Cavity Magnetron (J. Boyd)

The purpose of this investigation is to develop a voltage-tunable interdigital magnetron for operation in the microwave region. Dr. J. S. Needle has shown in Technical Report No. 11 that the circuit is one of the important parameters which limits the power output of a voltage-tunable magnetron. The desirable circuit characteristics as set forth in Technical Report No. 11 are low conductance and an inductive susceptance which varies slowly with frequency. It is further concluded, that if these circuit characteristics are "seen" by the electrons in the interaction space, the generation of significant microwave power is assured.

The use of the interdigital structure offers a good possibility of being able to realize the desired circuit characteristics. The Sylvania 3J22, an external-cavity interdigital magnetron which was designed for use in a mechanically-tunable resonator, has been used in several preliminary experiments. These experiments were conducted in order to determine the operating characteristics of this interdigital magnetron with various circuit arrangements. These experiments will now be discussed.

In the first experiment a mechanically-tunable rectangular cavity was used. The dimensions of the cavity are 2-1/2" x 5/16" x 7-1/2", the length is varied by movable plungers in both ends. The 3J22 was mounted in the center of this cavity and operating data taken for various positions of the plungers. It was found that the frequency of oscillation is determined entirely by the position of the plungers. The tube was mechanically tunable from 12 to 18 cm with a maximum c-w power output of 60 mw. This type of cavity has a high Q but does not meet the requirements of having an inductive susceptance which varies slowly with frequency. A magnetic loop-type coupling was used.

With the plungers removed and the cavity filled with steel wool, with short circuiting plates beyond the steel wool, it was possible to voltage tune the tube from 16 cm to 13.84 cm (7.8%). This range of tuning required only 100 volts change in plate voltage (from 700 to 800 volts). C-w maximum output of 140 mw was obtained. The lowering of the Q in this manner thus makes voltage tuning possible.

In the second experiment the 3J22 was mounted in the center of a 23-inch section of x-band waveguide. Magnetic loop coupling was used, the loop being placed very near the tube. The tube operated at a frequency below the cutoff frequency of the guide. Therefore the guide presented an inductive susceptance to the tube. Even though this susceptance is not a slowly varying function of frequency it was possible to voltage tune the tube from 17.27 cm at 720 volts to 12.48 cm at 960 volts (25 percent). A maximum c-w power output of 1.6 watts was obtained at an efficiency of 13.3 percent; however, in the region of 14 to 15 cm the power output was too small to be measured. The fact that the wave was attenuated very rapidly in the guide was demonstrated by using shorting plungers in the guide. As expected for operating frequencies below the guide cutoff frequency, it was found that the plungers did not affect the operation of the tube until they were brought very near the tube.

For experiment three the 3J22 was mounted in a section of 3" x 1-1/2" waveguide, which was connected at each end to a tapered-ridge-waveguide-to-coaxial-line junction (Fig. 6.1). One of the output terminals was connected through several feet of lossy line to a 50-ohm termination, and power for measuring was coupled out by means of the other coaxial terminal. On pulsed tests the tube operated from 5.78 cm to 13.85 cm (41 percent). The tube was then tested c-wand found to have operated over approximately this same range, with substantially constant power output. An attempt was made to obtain complete operating characteristics of the tube in this arrangement, however the tube failed before these tests were completed. Other tubes will be available in the near future. The incomplete c-w operating data show that the tube tuned from 14.02 cm at 1300 volts to 10.228 cm at 1500 volts (16.5 percent), with a power output of approximately 0.35 mw. The power output could be doubled by connecting the two output terminals together, utlilizing a line stretcher to adjust the phasing for maximum power.

Further tests with this arrangement are planned as soon as more 3J22 tubes are obtained.

The circuit arrangement used in experiment three seems to possess the characteristics necessary for voltage-tunable operation. With both ends of the waveguide matched to a 50-ohm coaxial line by means of a tapered-ridge waveguide, the admittance as "seen" by the electrons in the interaction space is determined by the type of termination used on the coaxial-line output terminals. The junctions used have a very wide band characteristic. Therefore, when the coaxial line is terminated in its characteristic impedance, "looking" into the waveguide the conductance is the characteristic conductance of the waveguide and the susceptance is a slowly varying function of frequency. The waveguide structure offers a good possiblity of obtaining the desired low conductance. Another requirement is that the capacity between adjacent anode teeth be as small as possible.

Plans are being made to design an interdigital magnetron which will operate in an external cavity similiar to that used in experiment

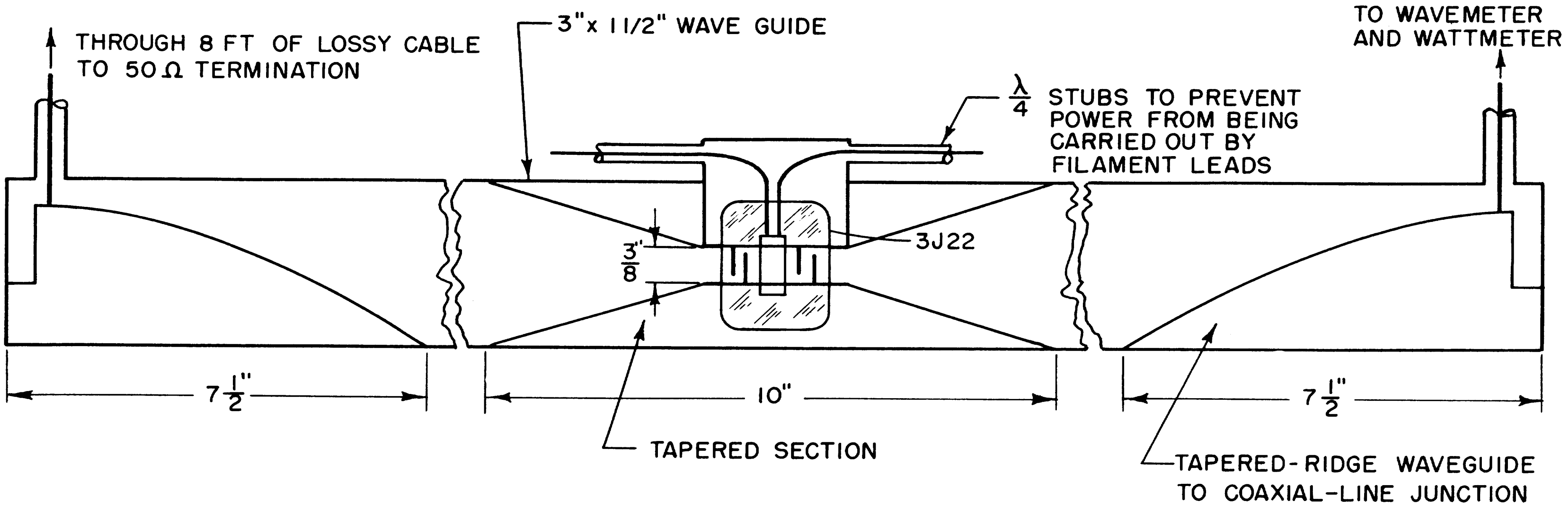

FIG. 6.1
SCHEMATIC DIAGRAM OF CIRCUIT
ARRANGEMENT USED IN EXPERIMENT NO. 3

three. The following specifications have been set up for this tube:

$E_p \leq 3000$ volts
$B < 2000$ gauss
$P_o = 5$ watts
$C_p \cong 1 \mu\mu f$
$\lambda = 10$ cm (center frequency)

7. The Trajectron: An Experimental D.-C. Magnetron (W. Peterson)

The main purpose of this experiment is to attain a more complete understanding of magnetrons by studying the space charge in a smooth-bore magnetron.

The tube which will be used for this experiment is a d-c smooth-bore magnetron with an electron gun in the same envelope arranged so that a beam of electrons can be sent into the space charge in an axial direction just grazing the cathode. The exit point of the beam will show on a fluorescent screen; thus, an electron's position as a function of time after it leaves the cathode may be measured. From this information electron velocities at any radius may be calculated and the space-charge distribution determined.

In the past the trajectron still could not be used in the manner for which it was designed. The difficulty in aligning the electron beam still has not been overcome. It appears that it would not be impossible to align the beam, but there is no apparent way of determining which way the gun should be moved to improve the alignment, i.e., no convergent sequence of adjustments has been devised. On one occasion, however, the beam was aligned approximately so that the spot could be seen on the fluorescent screen. The magnetron diode was operated at the same time, and a deflection of the spot was observed. However, the beam alignment was too poor to permit changing the beam velocity.

The a-c magnetic field of the heater was found to interfere with the beam, enlarging the spot on the fluorescent screen to a short line. This was overcome by commutating the filament voltage slowly and observing the spot while there was no filament current.

Stray electrons from the magnetron space charge struck the fluorescent screen causing a glow bright enough at the expected operating voltages to obliterate any spot from an electron beam. This difficulty was overcome by placing a fine copper mesh held at cathode potential just in front of the fluorescent screen.

The magnetron diode of the trajectron is working well, and the voltage-current data have been taken for various magnetic fields. The current cutoff is quite sharp, and it appears that it will be possible to operate the magnetron with the space-charge cloud near the anode while the electron beam is operating, giving a fairly large pattern on the fluorescent screen.

The magnetron voltage-current curves indicated points of negative resistances at voltages well below cutoff. Usually a single voltage-current curve showed several such points. (See Fig. 7.1) A set of data was taken locating the points and regions of negative resistance for various magnetic fields. These data are plotted in Fig. 7.2. The abcissa is the magnetic field and the ordinate is the radius of the space-charge cloud. This can be calculated from the magnetic field and the anode voltage by using the following formula:*

$$\frac{E_a}{B^2} = \frac{1}{8m} r_H^2 \, 2\left(1 - \frac{r_c^4}{r_H^4}\right) \ln \frac{r_a}{r_H} + \left(1 - \frac{r_c^2}{r_H^2}\right)^2$$

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* H. W. Welch, Jr., "Space-Charge Effects and Frequency Characteristics of C-W Magnetrons Relative to the Problem of Frequency Modulation," Technical Report No. 1, Electron Tube Laboratory, University of Michigan, Ann Arbor, November 15, 1948. Page 32.

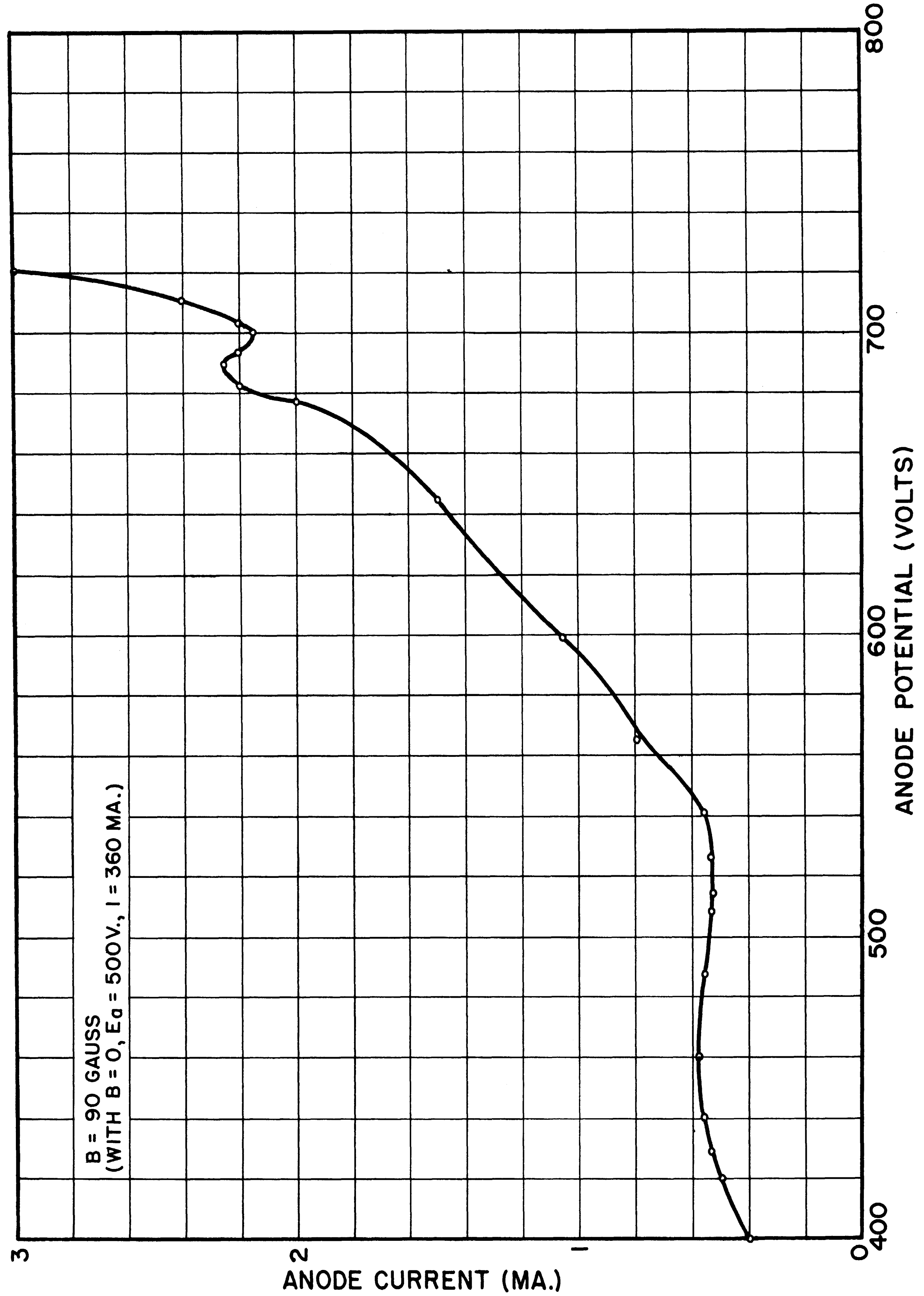

FIG. 7.1
TYPICAL MAGNETRON DIODE VOLT-AMPERE CURVE SHOWING NEGATIVE RESISTANCE

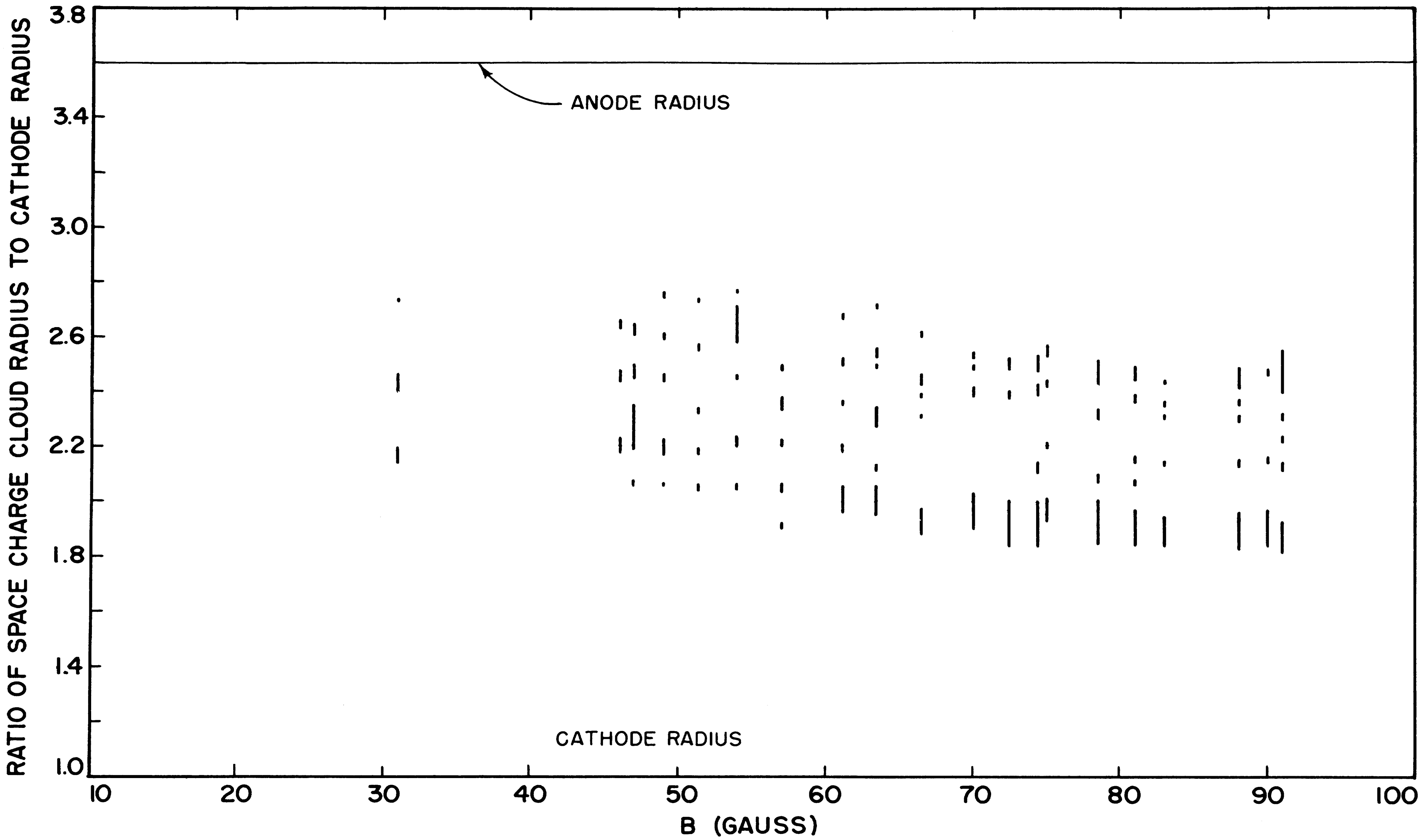

FIG. 7.2
POINTS WHERE NEGATIVE RESISTANCE HAS
BEEN OBSERVED IN THE MAGNETRON DIODE

where E_a = anode potential, r_a = anode radius, r_c = cathode radius, and r_H = space-charge-cloud radius. This equation is derived in Technical Report No. 1 assuming a single-stream solution but it holds very nearly for any sort of cutoff solution.*

It is rather interesting that all these regions and points of negative resistance occur when the space-charge radius is between 1.8 and 2.75. The points on this graph were taken with two different cathodes, and with several cathode temperatures. This small dependence on cathode temperature and magnetic field seems to indicate that this phenomenon is a d-c property of the space charge rather than one related to random velocities in the space charge. The experiment will be repeated with different anode radii to determine how this behavior depends upon the tube geometry.

8. Theoretical Analysis of Frequency Pushing and Voltage Tuning (H. W. Welch, Jr.)

In order to predict frequency pushing or voltage-tuning characteristics of a magnetron, it is necessary to provide a quantitative treatment of the phase-focusing process under large signal conditions. In section 7 of Quarterly Progress Report No. 3, 1951, a method for making such predictions was proposed and summarized. The assumptions involved in this technique have been carefully examined and a report is in preparation which will discuss in detail the large signal phase-focusing problem for the magnetron and the relationship of the phase-focusing mechanism to the r-f circuit admittance characteristic. This report also contains a survey of other treatments of the phase-focusing problem and of frequency characteristics of oscillatory magnetrons. The methods developed have been applied to

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* W. P. Allis, "Theory of the Magnetron Oscillator," Special Report No. V 9S (122), Radiation Laboratory, M.I.T., October, 1951.
J. C. Slater, Microwave Electronics, (Van Nostrand, New York, 1950), pp. 340 and 348.

typical experimental results obtained in the University of Michigan Laboratory and in other laboratories with encouraging agreement. This report is complete except for the treatment of experimental results. Since it will be issued within the next quarterly period the method will not be discussed here in further detail.* The report will be issued as Technical Report No. 12 entitled, "Dynamic Frequency Characteristic of the Magnetron Space Charge, Frequency Pushing and Voltage Tuning."

9. Conclusions (J. R. Black)

Three technical reports have been published in this period retarding to some extent the experimental progress.

Experimental results of the Model 9 insertion magnetron capable of either high-Q operation or low-Q voltage-tunable operation have been presented in Technical Report No. 11. Two new tubes constructed in an effort to (a) increase the frequency and (b) reduce the noise were tested. Complete tests on these tubes have not as yet been made. A parallel-plate slotted-line external circuit has been constructed which simplifies the mechanical problems involved in tuning coaxial lines.

A Model 8 high power tube having a parasitic mode suppressing the desired mode was tested. This tube is being rebuilt in order to eliminate the parasitic mode. A mechanically-tunable tube has been built and is on the pumps. This tube should provide information concerning the cathode choke or bypass design as well as information on parasitic operation.

The study of the Model 6 f-m and the Model 7 tubes has been brought to a point where this work can be dropped but can easily be resumed at a future date.

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* The method has been discussed in some detail with Mr. J. F. Hull of Evans Signal Laboratory at the Electron Tube Conference in June and in conference at Evans Signal Laboratory.

A new tube design for voltage-tunable operation is being studied. This will be an interdigital anode structure loaded by a waveguide matched to a load. This model will be designated as Model 13. Preliminary tests of the circuit employing a Sylvania 3J22 interdigital magnetron indicate that wide voltage-tunable operation can be obtained. Due to the high impedance between anode segments obtainable with this circuit, relative high power output with low noise is predicted.

Difficulties encountered with alignment of the exploring electron beam in the trajectron have so far prevented operation of the tube. Tests on the diode section show negative resistance characteristics in the below cutoff anode current and will be investigated further using different ratios of cathode-to-anode diameters.

The theoretical analysis of frequency pushing and voltage tuning is nearing completion.

10. Work in Prospect (J. R. Black)

The development of voltage-tunable tubes will receive the major attention of this laboratory. Problems involving the reduction of noise and the increase of power output of the Model 9 will be stressed. Work will continue on the development of the Model 13 voltage-tunable tube. The Model 8 rectangular tube and the trajectron will be worked on at a reduced rate. The theoretical analysis of frequency pushing and voltage tuning by Mr. H. W. Welch will be completed and published as Technical Report No. 12 during the next quarter.

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