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Title A SCALE MODEL OF AN OSCILLATOR FOR A 37-INCH CYCLOTRON

Abstract approved [redacted]
(Major Professor)

A one-quarter scale model of the oscillator to be used in the Oregon State College 37-inch cyclotron was constructed and tested. The tube used in the model was a 2C40 lighthouse triode with electronic characteristics similar to those of the RCA 5770 to be used in the full scale oscillator.

The self excited oscillator circuit used proved to be an excellent dee voltage source. It is a simple one tube circuit giving self protection in case of overloads, minimum possible parasitic circuits, good frequency stability, and a simple radio frequency coupling system.

A theoretical method was used to determine how nearly the characteristic impedance of the dee stems and the resonant impedance between the dees approached optimum values. The results indicate an increase in Z_0 of 20 to 25% over that used in the model is required to obtain optimum resonant impedance.

A SCALE MODEL OF AN OSCILLATOR FOR A 37-INCH CYCLOTRON

by

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A SCALE MODEL OF AN OSCILLATOR FOR A 37-INCH CYCLOTRON

INTRODUCTION

A vacuum tube is able to act as an oscillator because of its ability to amplify. Since the power consumed by the input of an amplifier tube is less than the amplified output, it is possible to make the amplifier supply its own input. When this is done, oscillations will be generated, and the tube will act as a power converter that changes the direct-current power supplied to the plate circuit into alternating-current power in the amplifier output.

Any amplifier arranged to supply its own input in the proper magnitude and phase will generate oscillations. Many circuits can be used for this purpose. In general, the voltage fed back from the output to the grid of the tube must be approximately 180° out of phase with the voltage existing across the load impedance in the plate circuit of the amplifier and must have a magnitude sufficient to produce the output power necessary to develop the input voltage.

The frequency at which oscillations occur is the frequency at which the voltage fed back from the plate circuit (i.e., tank circuit) to the grid is of exactly the proper phase to enable the tube to supply its own input. In oscillators associated in some way with a resonant circuit the frequency of oscillations approximates very closely the resonant frequency of this tank circuit.

In the usual case where a power oscillator is to develop a large amount of power at good efficiency, the tube is adjusted to operate as a Class C amplifier. The power output and plate efficiency then depend upon the grid-bias voltage, the tank circuit impedance, the maximum grid potential, the minimum plate potential, etc., exactly as in the case of a Class C amplifier.

A power oscillator normally uses grid-leak bias in order to insure that the oscillator will be self-starting. With a grid leak, there is no bias when the electrode voltages are first applied, so that the tube then has a high transconductance and is in a condition to amplify. Any thermal agitation voltage of the proper frequency will accordingly start the oscillations building up. (4, pp. 192-193)

For many requirements it is essential that the generated frequency be as nearly constant as possible. The first step in achieving this is to maintain constant the resonant frequency of the tank circuit. Factors that can cause the resonant frequency to change are ageing of circuit components, variation of inductance and capacitance with temperature in both circuit elements and tube elements, and variations in the reactance that the load couples into the tuned circuit. (4, pp. 197-198)

The most important factor in obtaining a stable frequency is the use of a tank circuit having a high effective Q. This is because the frequency change required to develop the phase shift that compensates for variations in load resistance, tube voltages and other such variables, is inversely proportional to the tank-circuit Q. Frequency stability is also helped by operating the tube so that the grid current is small and constant (as with a high grid-leak resistance) and by operating the oscillator with a conservative power output.

When frequency stability is important, the load impedance that is coupled into the tank circuit should be as nearly resistive as possible. This is because reactance coupled into the tank circuit greatly alters the resonant frequency, whereas coupled resistance has only a slight effect.

The frequency of oscillators operating at very high frequencies is often controlled by a resonant transmission line. This is possible because a quarter-wave transmission line short-circuited at one end acts as either a parallel or a series resonant circuit.

The resonant-line oscillator is able to generate large amounts of power with good frequency stability, without the use of an additional power amplifier. Resonant-line oscillators are suitable only when the wave length is small enough for the lines to be of reasonable physical size. (4, pp. 197-202)

The effect on frequency of unavoidable variations in tube capacity can be minimized by arranging the oscillator circuits so that the electrostatic energy stored in the tube capacities is as small as possible compared with the total electrostatic energy stored in the resonant circuit. This means a high circuit Q, the highest possible ratio of transconductance to changes in tube capacities, and the smallest possible coupling from the tank circuit to the grid and plate electrodes of the tube that will permit oscillations to be maintained. This can be done in resonant line oscillators by connecting the grid so that the section of the line between grid and cathode is only a small portion of the total electrical length of the line measured from the voltage node.

If the tube and line can be so arranged that the tube electrodes become extensions of resonant-line tank elements, it is possible to allow the tube elements to be a considerable percent of the electrical length of the line and thus operate at higher frequencies. (5, pp.485)

At the higher frequencies used with resonant-line circuits it is not possible to ground the cathode directly by means of a by-pass condenser, as at lower frequencies, because of the cathode lead reactance. In order to obtain proper circuit operation, it is accordingly desirable either to employ a half-wave-length line between cathode and ground or to isolate the cathode from ground by means of a choke or a quarter-wave-length line. (5, pp.517)

The curve of resonant-line impedance as a function of frequency in the region near resonance has the same shape as a series resonance curve, with an equivalent Q given by the formula

$$Q = \frac{2\pi Z_o f}{R c} \qquad (1)$$

where Z_o = characteristic impedance of line in ohms

f = frequency in cycles per second

R = radio frequency line resistance per unit length

c = velocity of light in the same units of length as R.

A transmission line acts as a voltage step-up device when the receiver is open-circuited and is an odd number of quarter wave lengths from the generator. At frequencies near resonance, the step-up varies with frequency in exactly the same manner as a resonance curve having an equivalent Q given by equation (1). The voltage step-up ratio is $Q \times 4/\pi n$ instead of Q, as in the case of the ordinary series resonant circuit. Here, n is the number of quarter wave lengths in the line.

A line can serve as a low-loss inductance or capacitance by employing the proper combination of length, frequency, and termination. Thus, with an open-circuited receiver a line will offer a capacitive reactance when less than a quarter wave length long and an inductive reactance when between a quarter and a half wave length long. The reactances are:

$$X_s = -j \frac{Z_o}{\tan (2\pi l/\lambda)} \qquad (2)$$

where l/λ is the line length measured in wave lengths.

The Q of the reactance is related to the Q of the resonance curve of the corresponding quarter-wave line by the equation (5, pp. 191-193).

$$\frac{\text{Q of reactance}}{\text{Q of resonant quarter-wave line}} = \frac{\sin (4\pi l/\lambda)}{2\pi\, l/\lambda} \qquad (3)$$

It should be pointed out here that short-shorted lines used as series-resonant, capacity-loaded tank-circuit elements are used as the series inductance of the tank-circuit when less than a quarter wave long.

This thesis deals with the design, construction and testing of a scale model oscillator from which some of the characteristics of an oscillator suitable for exciting a pair of 32 inch dees in a 37 inch cyclotron may be determined.

The relation between the oscillator and the cyclotron is that the oscillator lines are capacity loaded by the accelerating electrodes, or dees, of the cyclotron making it necessary to shape these dees so as to have a dee to dee capacitance through ground within the range required for satisfactory oscillator operation.

The design of the 37 inch cyclotron being constructed by Oregon State College includes an oscillator which uses short-shorted stubs of high resonant impedance. This oscillator is a self-excited type with unique electronic design particularly applicable to cyclotron operation. It was designed by W. R. Baker at the University of California Radiation Laboratory, Berkeley, California.

The cyclotron uses a positive-atomic-particle acceleration chamber consisting of two semicylindrical "dees" which are insulated from each other in a vacuum chamber located between the pole faces of a large electromagnet. A radio frequency voltage of about 10 megacycles per second (for deuterons) at approximately 100 kilovolts is applied between the dees to furnish a periodic electrostatic accelerating potential to the atomic particles rotating in a plane perpendicular to the magnetic field. The radius of rotation is thus periodically increased until the high energy particles are extracted from the cyclotron for some intended use.

The insulated dee supports, or dee stems, must enter the vacuum chamber through air tight bushings capable of withstanding the high potential radio frequency voltage with minimum losses. Because of the shape and location of these stems, they lend themselves easily to be used as the two conductors of a radio frequency transmission line. This line can be resonated with the capacitance offered by the dees at some desirable frequency and thus become a part of a radio frequency tank circuit or coupling system.

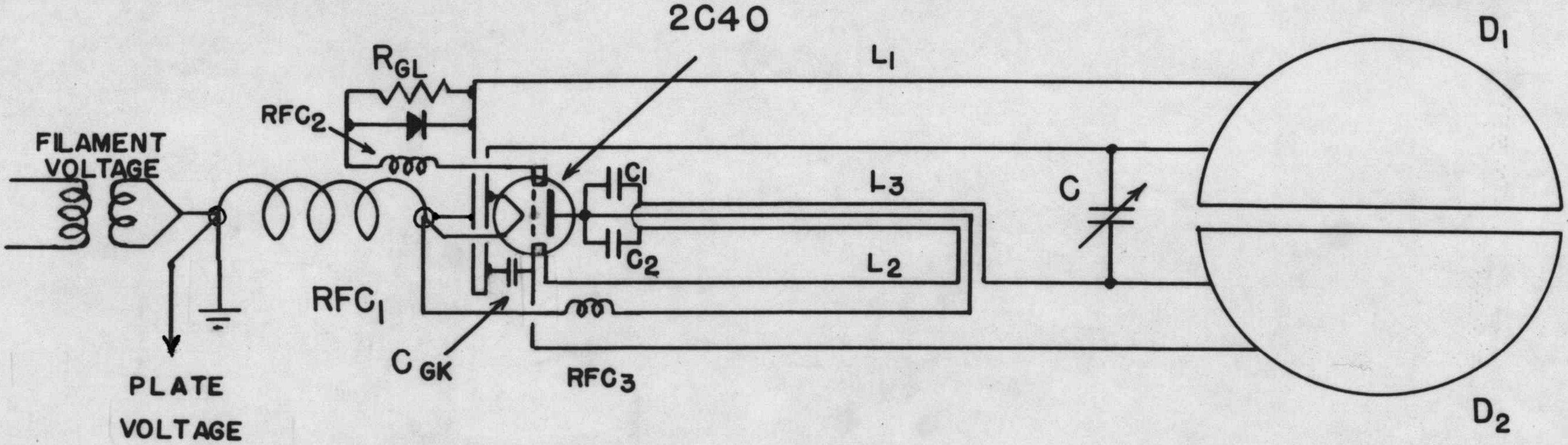
The fundamental principle that allows the cyclotron to work is the fact that the time required for a charged particle to make one complete turn within the dees is the same for all speeds. This is true only when relativistic effects are neglected.

The periodic acceleration of ions requires a powerful, stable, tunable oscillator of simple design efficiently coupled to the accelerating dees. The investigation of a model of such an oscillator is necessary to obtain information leading to the desired optimum design.

OSCILLATOR CIRCUIT AND OPERATION

The circuit of the oscillator is shown in Figure 1. The dees, D_1, D_2, form a capacitive load across the ends of a pair of transmission lines, L_1, L_2, which are shorter than a quarter wave length and are joined together by a low inductance capacitor, C_{gk}, at the oscillator cathode. The transmission lines serve as dee stems supporting the dees and form a part of the resonant system. The capacitance C_{gk} effectively connects the dee stems together to form the inductance that resonates with the dee capacitance thus forming the oscillator tank circuit. It also forms a capacitive voltage divider with the dee capacitance to provide a low impedance driving source for the oscillator grid. The magnitude of the grid driving voltage is determined by the capacitive reactance of this condenser and the current through it and is applied between grid and cathode in proper phase to sustain oscillations. The filament current is supplied coaxially through an isolating choke, RFC_1, connected to the mid-point (zero voltage) between the dees thus eliminating the necessity for any fixed radio frequency grounds. This floating ground and low-inductance low-impedance source of grid drive voltage eliminates parasitic circuits that might cause unwanted modes of oscillation.

Another lead inside the filament choke supplies power through the grid dee stem, L_2, and adjustable plate coupling loop, L_3, to the anode of the oscillator tube. Capacitors C_1 and C_2 block the direct current from the dee stem system. The direct current lead has a radio-frequency choke, RFC_3, mounted inside the grid dee stem to block the radio-



OSCILLATOR CIRCUIT
FIGURE I

frequency grid voltage between that stem and the filament choke. This lead must be insulated to withstand the direct current plate potential. The grid bias is developed across the grid leak resistance, R_{gl}, through the grid choke, RFC_2. The rectifier in parallel with R_{gl} is used to keep the average grid potential from going positive.

It is possible for the tube to oscillate as a tuned-plate tuned-grid oscillator at very high frequencies using the grid choke as the grid resonating element. This type of parasitic can be eliminated by proper grid choke design and by keeping the plate coupling loop reasonably long.

When power is taken out of any resonant circuit, there is an increase in the effective resistance in series with the circuit. When subjected to excessive overload this will cause the tube in this type of oscillator to cease oscillating. If the overload is in the form of an arc, the arc will be extinguished and the rise in plate current due to loss of grid bias will restart the oscillations immediately. However, if the overload is a metallic short between a dee stem and ground or between the dees, the plate supply will have to contain an overload protective device in order to prevent damage to the tube.

In order to tune the oscillator, vacuum capacitors may be connected between each stem and ground at the point where the dee stems go through the vacuum chamber wall. Any change in oscillator frequency will necessitate changing the value of the capacitance C_{gk} so as to keep its reactance constant thus keeping a constant driving voltage on the oscillator tube. These tuning condensers need not be matched, nor do the dee to ground capacitances. Considerable unbalance may be tolerated because the radio frequency system floats with respect to ground. (1.)

OSCILLATOR DESIGN SPECIFICATIONS

Dimensions of the oscillator were determined by scaling the preliminary design of the oscillator for the Oregon State College cyclotron. These dimensions constituted a logical beginning and were changed in some cases when investigation showed this to be desirable.

TABLE I

	FULL SCALE	QUARTER SCALE
Deuteron Frequency	10.75 mc	43 mc
Proton Frequency	21.5 mc	86 mc
Dee Diameter	32"	8"
Dee Thickness	4"	1"
Dee to Dee Spacing	2"	1/2"
Dee to Chamber Spacing	1/2"	1/8"
Stem Diameter	6.5"	1.625"
Stem Spacing (centers)	19.5"	4.875"
Shield Width (inside)	39"	9.75"
Shield Height (inside)	19.5"	4.875"
Chamber Height (inside)	5"	1 1/4"
Chamber Width (inside)	39"	9.75"
Chamber Length (inside)	41.8"	10.45"
Dee Center to Chamber End	22.32"	5.58"
Closest approach Dee to Chamber	3.5"	0.875"
Power for 100 μa 10 mev beam	10 KW	

Table I - continued

	FULL SCALE	QUARTER SCALE
Tube	5770 RCA	2C40
Dee to Dee Voltage	100 KV	

The following tabulations are found by use of the above list:

Wave length, λ_D, (for deterons)	27.9 meters	6.973 meters
Wave length, λ_P, (for protons)	13.95 meters	3.486 meters
λ_D	274.5"	68.7"
λ_P	137.3"	34.35"
Space between Stems	13"	3.25"
Dee Capacitance to ground (each)	360 $\mu\mu$fd	90 $\mu\mu$fd
Dee to Dee Capacitance through ground	180 $\mu\mu$fd	45 $\mu\mu$fd

Figure 2 shows the dimensions of the dee stems in relation to the oscillator shield. This system will have a characteristic impedance of 138.2 ohms regardless of size provided that the ratios of dimensions remain as shown in Figure 2.

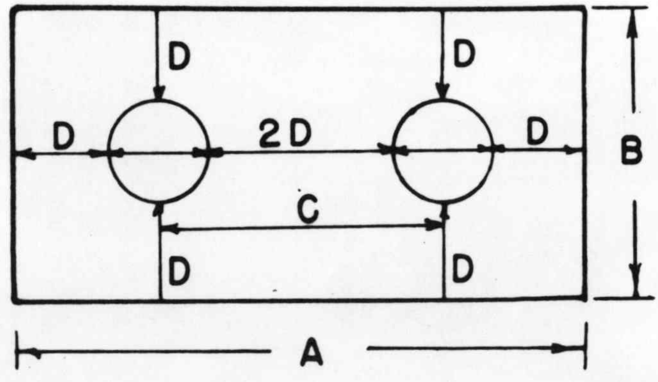


FIG. 2

From the figure we see:

$$A = 6D$$

$$B = C = 3D = A/2$$

for $$A = 39'' \quad \text{then}$$

$$B = 19.5''$$

$$C = 19.5''$$

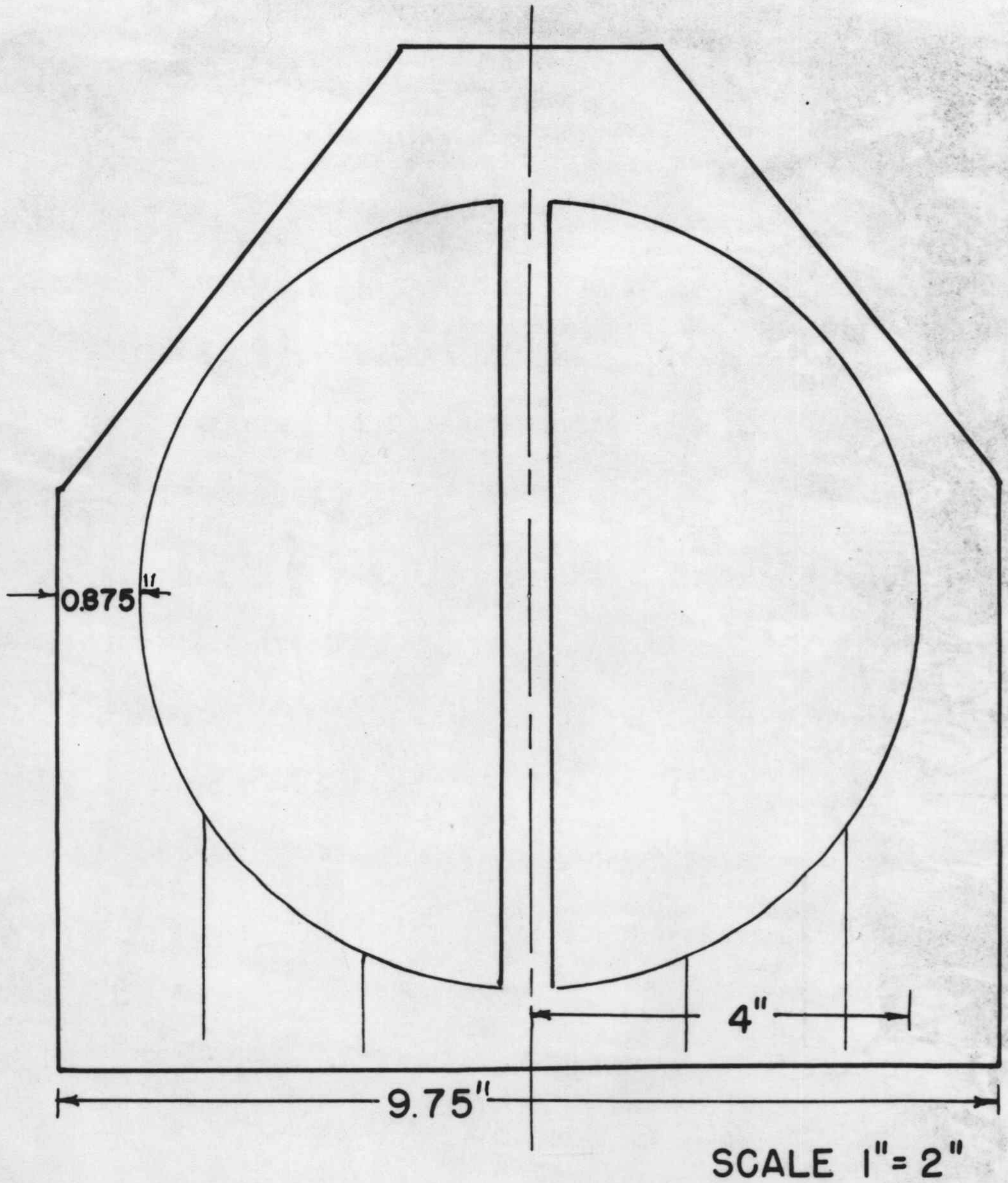
$$D = 6.5''$$

$$2D = 13''$$

Information concerning the characteristics and limitations of the oscillator is desired. The dimensions of the cyclotron building limit the length of the oscillator shielding to approximately thirteen and one half feet. Design of the stems will take on special significance if the required stem length is longer than about twelve feet (leaving passage room between the wall and the stems).

The effect of the plate coupling loop makes a complete mathematical solution of the oscillator very difficult. Solution of the characteristic impedance of the shorted transmission-line dee-stem system is thus impossible by any of the commonly known equations. Because the plate coupling loop is adjustable in length and the oscillator output voltage is variable with drive, the angle of plate current flow, frequency, degree of coupling, oscillator efficiency and dee to dee voltage become variables with very complex relationships. This problem will be handled in a manner deemed satisfactory to the situation.

Figure 3 is a plan view of the dee chamber and dees showing placement of dees with respect to the chamber walls.



DEE CHAMBER SHOWING PLACEMENT

FIG 3

ASSOCIATED EQUIPMENT

The 6.3v alternating-current filament voltage was supplied through a transformer from the building lighting circuit without any attempt at stabilization.

The plate circuit direct-current power source was an electronically regulated variable-voltage power supply used primarily to stabilize variations in line voltage. This equipment gave excellent control and gratifying results were obtained when repeat data were taken.

Frequency measurements were made with a BC-221 heterodyne frequency meter powered by a regulated 150 volt direct current power supply. The accuracy of this instrument is better than 0.05 percent. A Hallicrafters communication type receiver was used to locate the approximate oscillator frequency before measurements were made with the BC-221.

A Millen Company grid-dip oscillator was used for checking the resonant frequency of the circuit when the dee stem length was changed and for locating parasitic frequencies and circuits. The accuracy of this instrument is within the range of three to four percent but its usefulness for quick checking made it nearly indispensable.

An inductive loop with a 1N21 crystal diode as a detector was used for detecting radio frequency energy on the system. The current in the detector was kept below 60 microamperes to keep it proportional to the the square of the voltage and hence to the radio frequency power in the system. This loop was not allowed to resonate at the operating frequency thus, when the frequency did change, the effect on the detected current was negligible.

A Hewlett-Packard Model 400-C vacuum tube voltmeter was used for voltage measurements at the frequency of operation. Both capacitive-probe pickup and direct-contact were tried for measurement of radio frequency voltage on the dees. These measurements were not successful because the diode in the voltmeter probe so heavily loaded the oscillator when contact was made with the dees that the oscillator's operation was unstable.

The failure to measure the radio frequency voltage on the dees by means of the model 400-C vacuum tube voltmeter resulted in the design of a resonant high-impedance transmission line voltage indicator as follows. (6, pp. 749-752)

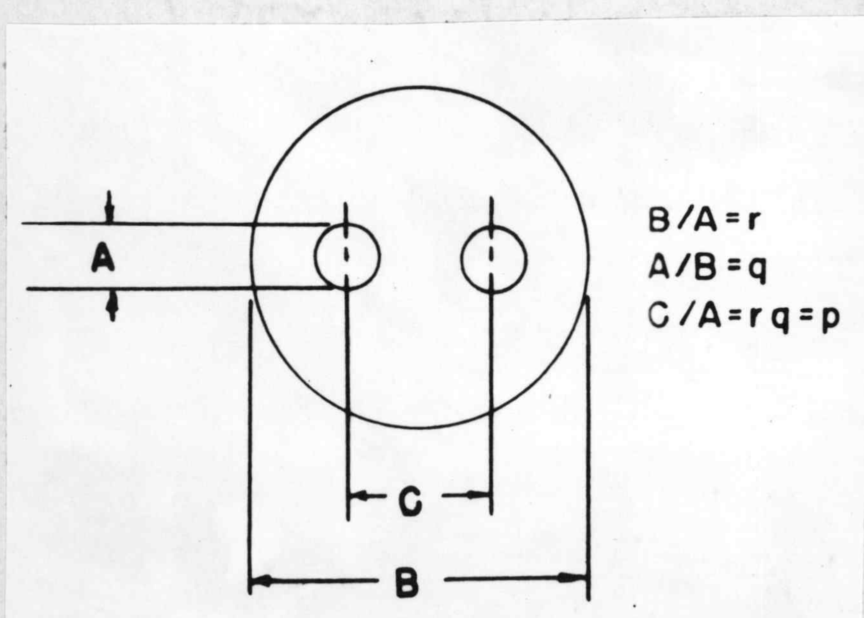


Figure 4

The characteristic impedance of the transmission line shown in Figure 4 is:

$$Z_o = 120\left\{ \ln\left[2p\,\frac{(1-q^2)}{(1+q^2)}\right] - \frac{1+4p^2}{16p^4}\,(1-4q^2)\right\} \tag{4}$$

The unloaded tank impedance is:

$$R_o = \frac{4\pi Z_o^{\,2}}{R_s\,\lambda}\left[\frac{1-\cos(4\pi\,\ell/\lambda)}{(4\pi\,\ell/\lambda) + \sin(4\pi\,\ell/\lambda)}\right],$$

$$= 4.19 \times 10^{-4}\,(fZ_o^2\,/\,R_s)\,\phi(\ell/\lambda). \tag{5}$$

The series resistance of the line in ohms per centimeter is:

$$R_s \cong \frac{\rho_s}{\pi B}\left\{ r\left[1+\frac{1+2p^2}{4p^4}\,(1-4q^2)\right] + 4q^2\left[1+q^2-\frac{1+4p^2}{8p^4}\right]\right\}$$

$$\cong 1.66 \times 10^{-4}\,\frac{f^{1/2}}{B}\left\{ r\left[1+\frac{1+2p^2}{4p^4}\,(1-4q^2)\right] + 4q^2\left[1+q^2-\frac{1+4p^2}{8p^4}\right.\right\} \tag{6}$$

The unloaded tank circuit Q is:

$$Q = \frac{1}{2(\Delta f/f_o)} = \frac{4\pi f Z_o}{6 \times 10^4\,R_s},$$

$$= 2.09 \times 10^{-4}\,f\,(Z_o\,/\,R_s) \tag{7}$$

where, for the above equations,

ℓ = length of line in centimeters

λ = wavelength in centimeters

f = resonant frequency in megacycles per second

ρ_s = skin effect surface resistivity of conductor in ohms per square centimeter.

In all of these equations, R_s is an important factor which depends on ρ_s. From reference 6 for copper,

$$\rho_s = 2.61 \times 10^{-4} f^{1/2} \tag{8}$$

Equations (4), (5) and (8) for copper can then be reduced to functions of line dimensions, $\phi(\ell/\lambda)$, $\theta(r, q)$, $\psi(r, q)$.

Thus, for copper equation (4) becomes

$$Z_o = f(r, q)$$

equation (5) becomes

$$R_o = Bf^{1/2}\,\psi(A, B, C, \cdots,)\,\phi(\ell/\lambda),$$

and equation (7) becomes

$$Q = Bf^{1/2}\,\theta(r, q) \quad \text{or}$$

$$Q = Bf^{1/2}\,\theta(A, B, C, \cdots) \text{ which is independent of } \ell. \tag{9}$$

For any of the above, the attenuation

$$\alpha = R_s / 2Z_o \tag{10}$$

thus maximum selectivity also means maximum efficiency of the tank circuit.

The desire for causing minimum loading of the oscillator when contact is made by the resonant voltmeter on the dees, requires the design of the resonant voltmeter to be entered with conditions allowing maximum R_o.

From Figure 5 of reference 6 we see that the function $\psi(r, q)$ has a maximum for values of

$$r = 15$$
and
$$q = 0.5$$

and $\Psi(r, q)$ = 10.9 kilohms. Figure 2 of reference 6 shows $\phi(\ell/\lambda)$ is a maximum for ℓ/λ = 0.25 and $\phi(\ell/\lambda)$ = 0.64.

From Figure 6 of reference 6, when r = 15 and q = 0.5, the function $\phi(r, q) = 20.5$ which is not the condition required for maximum Q. Thus, for maximum unloaded tank impedance of a quarter wave line, we do not have maximum tank efficiency.

The design requirements show for

r = 15 and q = 0.5, that the other line dimensions are as follows:

B = 3.89 cm as set by shield material available.

$A = {}^{B}/_{r} = 3.89/15$

A = 0.2595 cm

The available material with a dimension close to 0.2595 cm for use as the leads was some welding rod which measured 0.2425 centimeters in diameter.

The resonant voltmeter thus has dimensions as follows:

A = 0.2425 cm

B = 3.89 cm

r = b/a = 16.03 = 16

q = 0.5

C = bq = 1.95 cm

p = c/a = rq = 8.04

$2p = 16.08,\ 2p^2 = 129.2,\ 4p^2 = 258.5$

$16p^2 = 66{,}700,\ 8p^4 = 33{,}330,\ 4p^4 = 16{,}670$

The characteristics of the line can now be determined.

$$Z_o \cong 120\left\{ \ln\left[16.08 \ \frac{0.75}{1.25}\right] - \frac{259.5}{66,700}\,(0)\right\}$$

$$= 262 \text{ ohms}$$

A check on Figure 4 of reference 6 shows Z_o = 262 ohms.

$$Q = Bf^{1/2} \ \Theta(r, q) \quad , \qquad f = 43 \text{ mc}$$

$$Q = (3.89)\ (6.56)\ (21)$$

$$Q = 536$$

$$R_o = (4.19 \times 10^{-4})\ (f\ {}^{Z_o}/R_s)\ \ \phi(\ell/\lambda)$$

$$R_s = 1.66 \times 10^{-4}\ \frac{16.02}{3.89}\left\{16\left[1 + \frac{130.2}{16,670}\ (0)\right] + 1\left[1.25 - \frac{259.5}{33,330}\right]\right\}$$

$$= (6.84 \times 10^{-4})\ (16 + 1.242)$$

$$= 117.9 \times 10^{-4} \text{ ohms}$$

$$R_o = (4.19 \times 10^{-4})\ \left[(43)\ (262)^2 \ / \ (117.9 \times 10^{-4})\right]\ (0.64)$$

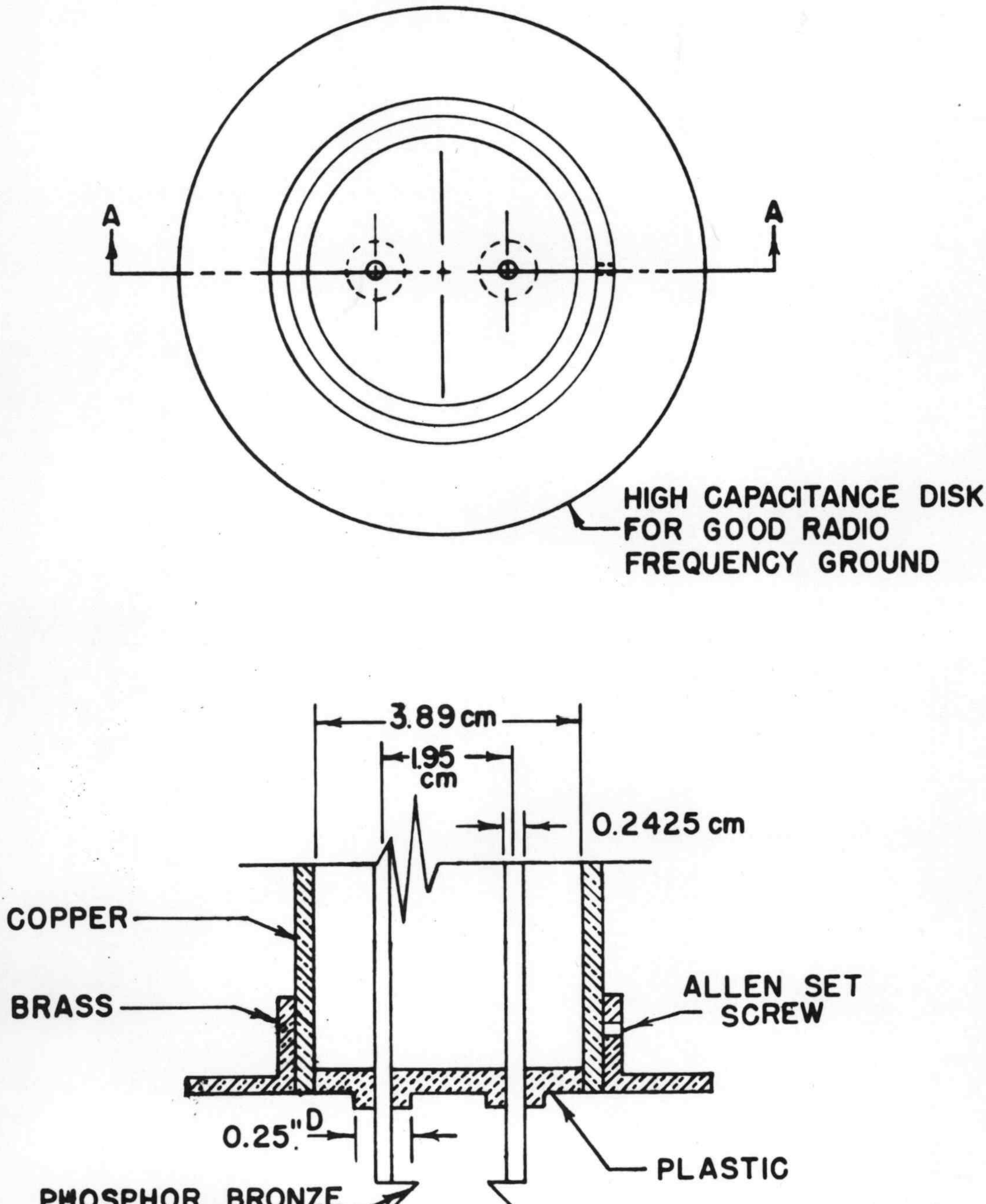
$$= 67,250 \text{ ohms}$$

Construction of voltmeter.

The two conductors, Figure 5, were spaced by thin circular sheets of polystyrene each with two small holes drilled 1.95 centimeters center to center. These spacers were separated far enough from each other to make their effect on the characteristic impedance of the line negligible. Contact was made to the dees with two small pointed phosphor-bronze spring tips soldered to the ends of the lines and inserted through holes in the top of the vacuum chamber.

The length of the quarter wave lines was made adjustable by a sliding, shorting ring at one end of the long shield. The length was adjusted by making the frequency of the model oscillator the same as when the resonant voltmeter was not used in order to be sure there was no reactance between the contacting ends of the resonant voltmeter at the operating frequency. The radio frequency short-circuit in this sliding ring had to be also an open circuit to direct current to prevent shorting the oscillator grid bias which exists between the dees. It consisted of two 0.01 $\mu\mu$fd mica condensers, one on each line to ground. A sensitive Western Electric 400 ohm radio frequency vacuum thermocouple was connected in parallel with the shorting condensers, which had sufficient voltage drop to cause several microamperes of direct current to flow in the thermocouple metering circuit when the oscillator power input was in the neighborhood of two watts.

The resulting device was thus a fairly high impedance, zero reactance, resonant voltmeter, whose output current was a function of power. This current was measured by a Weston 15 microampere instrument with a variable bucking voltage to extend the range of the current measured and to increase the sensitivity, as shown in Figure 6. It was desired to measure not the magnitude of the voltage between the dees but the percentage of change of this voltage along the edges of the dees. This change in voltage is a very small percentage of the total voltage, thus a very sensitive device is needed. Scale factors which resulted from this type of bucking-current sensitivity-multiplier are recorded so that while the full scale reading of the instrument was only 15 microamperes, the data may be extrapolated to several times this value.

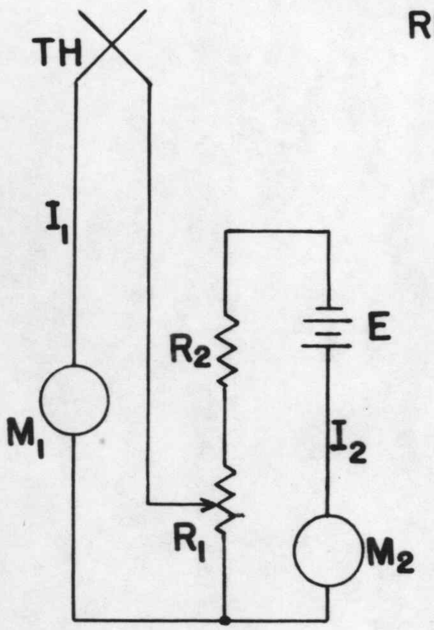


SECTION A-A

RESONANT VOLTMETER

FIG. 5

SCALE EXTENSION CIRCUIT FOR RESONANT VOLTMETER



R_{M1} = 106.57 OHMS

R_{TH} = 400 OHMS

R_1 = 4.5 OHMS

R_2 = 50 OHMS

E = 1.5 VOLTS

I_1 = 0 TO 15 MICROAMPERES

I_2 = 2.5 MILLIAMPERES

FIGURE 6

ELECTRONIC CHARACTERISTICS OF UNSHIELDED OSCILLATOR

The first investigation was made to determine the electronic characteristics of the model oscillator. The shielding and chamber were not used because of difficult access when fully shielded. Instead, the 64 inch dee stems required for a frequency of 43 mc were supported on a table top and care used to minimize movement of conducting objects in the room.

The power output from the system was determined arbitrarily by measuring the current in a crystal detector in an untuned loop placed near the maximum current point of the system. This current is designated as I_o in the data. The resistance of this load is unknown but the coupling of the load was always adjusted so that any increase in coupling caused an increase in the direct current power input to the oscillator. The current I_o may be taken as a measure of the amplitude of oscillations, being a maximum only for optimum conditions and is also a function of the oscillator efficiency and Q of the system.

Graphs 1 and 2 show the effects of grid driving voltage and grid bias upon plate supply voltage for constant plate current. The slopes and indicated effects would be reversed if the plate supply voltage had been held constant.

In order to determine the length of the plate coupling loop desired for optimum operation, power input and grid bias were taken as functions of loop length, all other parameters being held constant. Graphs 3, 4 and 9 show that conditions for maximum oscillations require a definite length

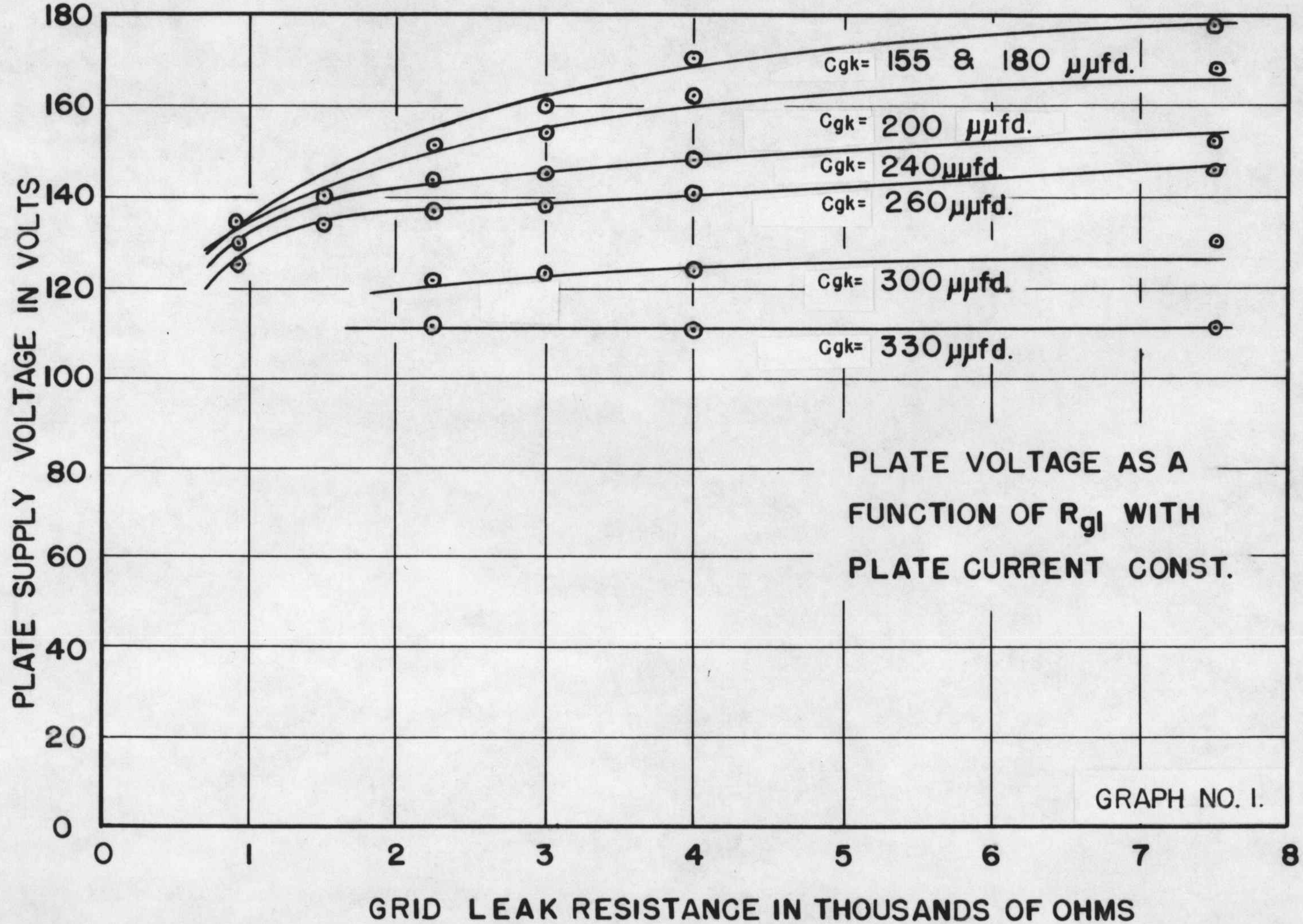
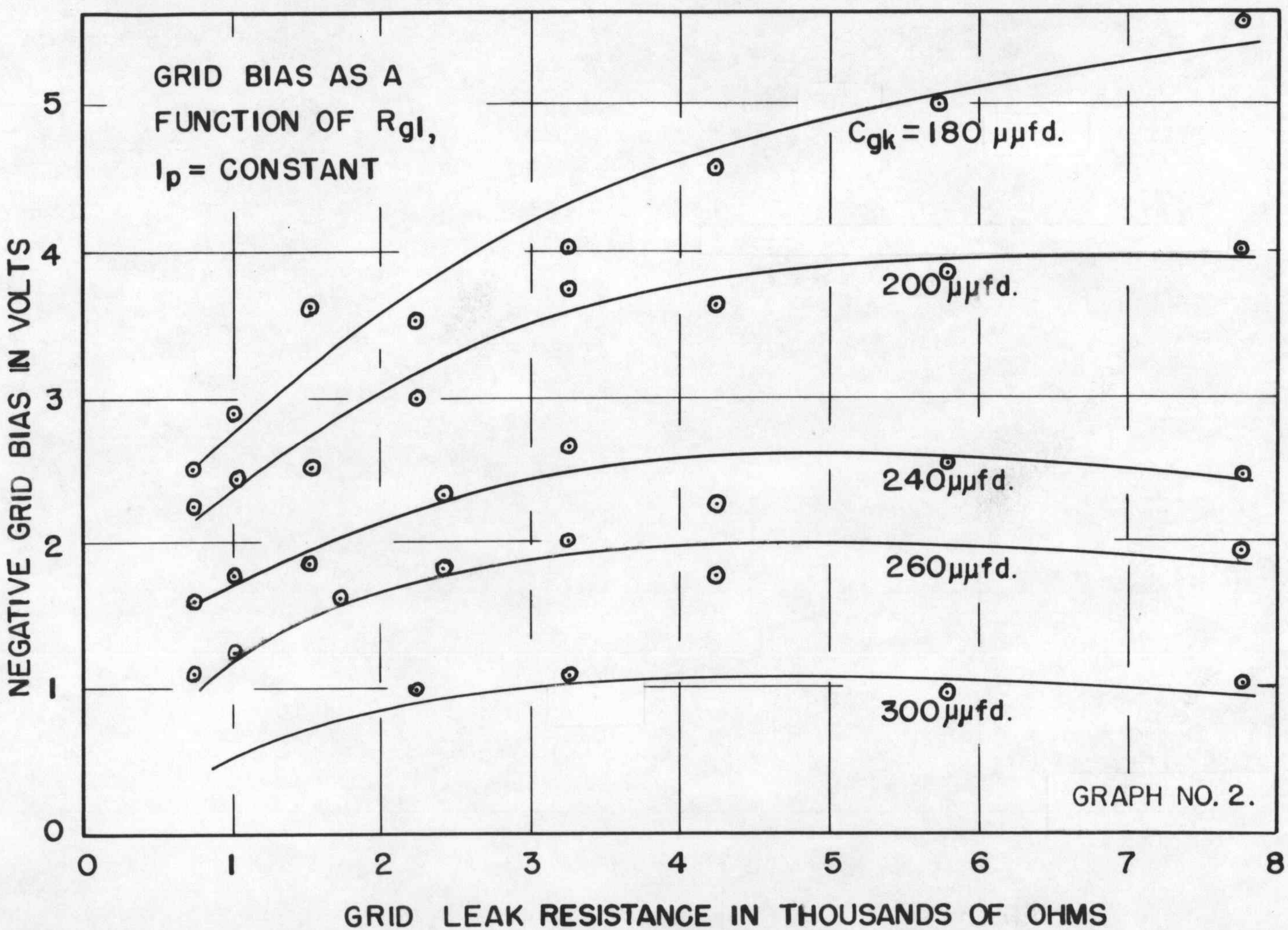
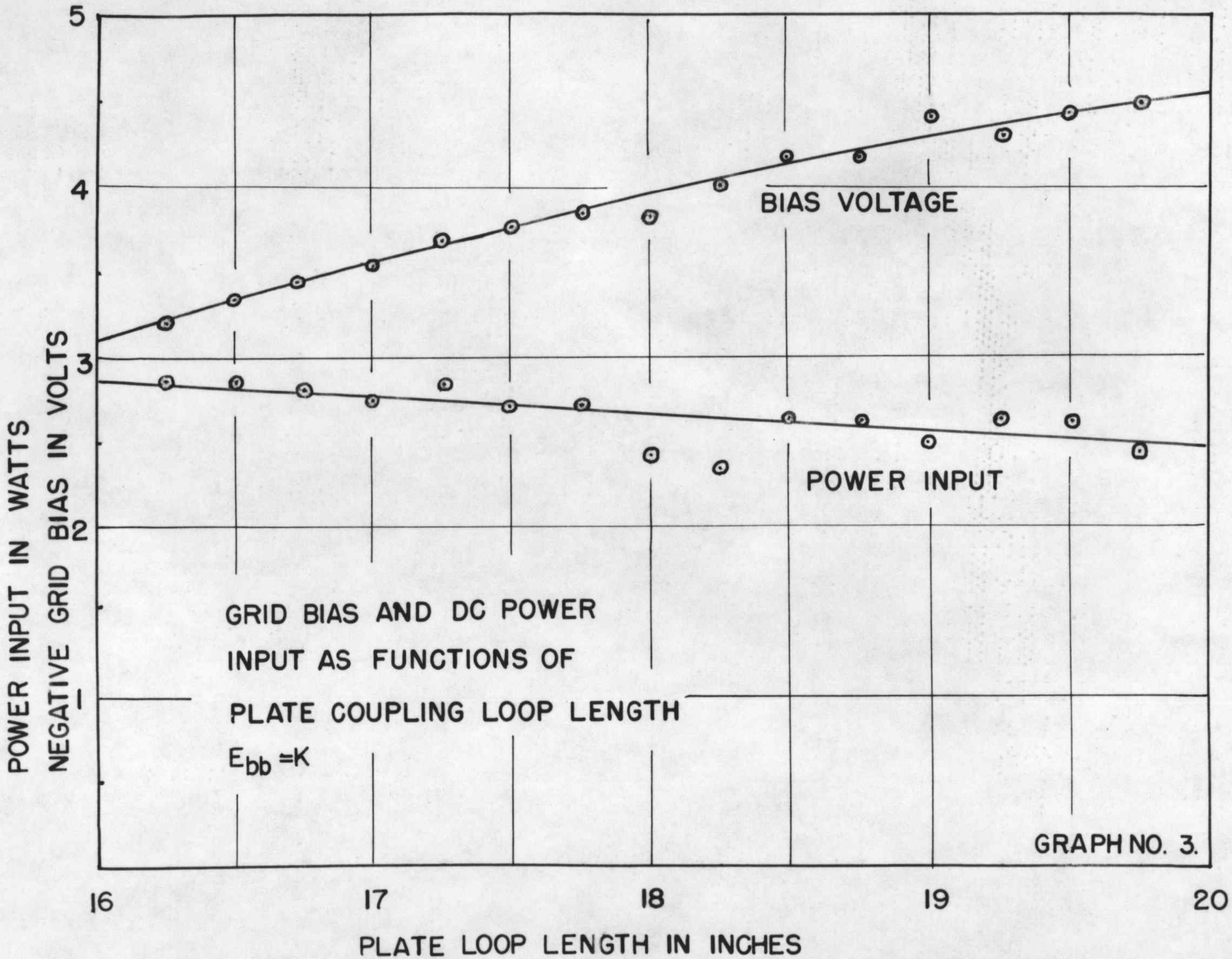
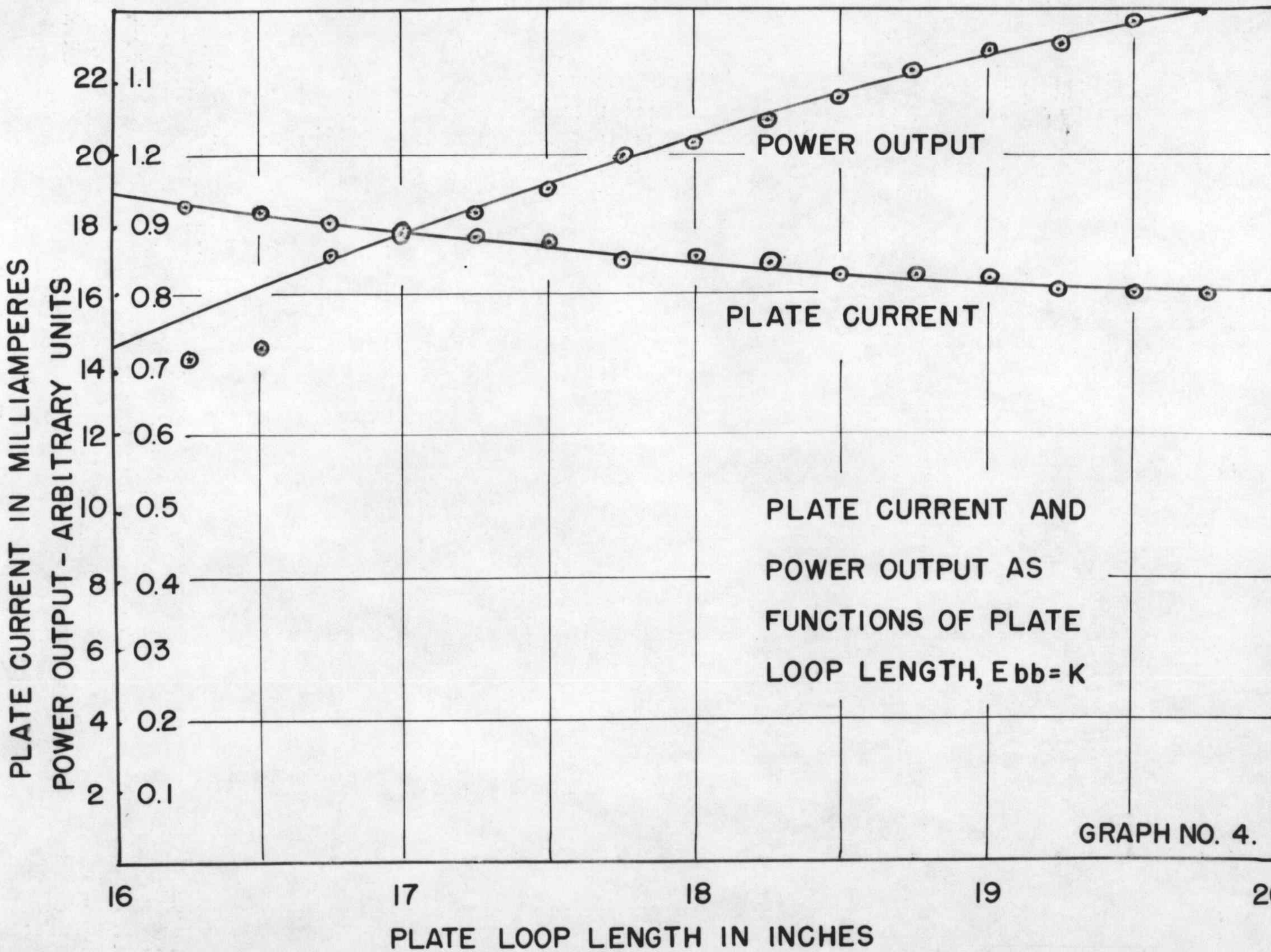


PLATE SUPPLY VOLTAGE IN VOLTS
GRID LEAK RESISTANCE IN THOUSANDS OF OHMS
Cgk= 155 & 180 μμfd.
Cgk= 200 μμfd.
Cgk= 240 μμfd.
Cgk= 260 μμfd.
Cgk= 300 μμfd.
Cgk= 330 μμfd.
PLATE VOLTAGE AS A
FUNCTION OF R_{gl} WITH
PLATE CURRENT CONST.
GRAPH NO. 1.


GRID BIAS AS A
FUNCTION OF R_{gl},
I_p = CONSTANT
C_{gk} = 180 μμfd.
200 μμfd.
240 μμfd.
260 μμfd.
300 μμfd.
GRAPH NO. 2.
NEGATIVE GRID BIAS IN VOLTS
GRID LEAK RESISTANCE IN THOUSANDS OF OHMS
0
1
2
3
4
5
6
7
8


5
4
3
2
1
16
17
18
19
20
BIAS VOLTAGE
POWER INPUT
POWER INPUT IN WATTS
NEGATIVE GRID BIAS IN VOLTS
PLATE LOOP LENGTH IN INCHES
GRID BIAS AND DC POWER
INPUT AS FUNCTIONS OF
PLATE COUPLING LOOP LENGTH
$E_{bb} = K$
GRAPH NO. 3.



POWER OUTPUT
PLATE CURRENT
PLATE CURRENT AND
POWER OUTPUT AS
FUNCTIONS OF PLATE
LOOP LENGTH, Ebb = K
GRAPH NO. 4.
PLATE CURRENT IN MILLIAMPERES
POWER OUTPUT - ARBITRARY UNITS
22 1.1
20 1.2
18 0.9
16 0.8
14 0.7
12 0.6
10 0.5
8 0.4
6 03
4 0.2
2 0.1
16
17
18
19
20
PLATE LOOP LENGTH IN INCHES

of loop which is to be expected since the plate coupling loop adjusts the degree of coupling and matches the plate impedance of the oscillator to the dees.

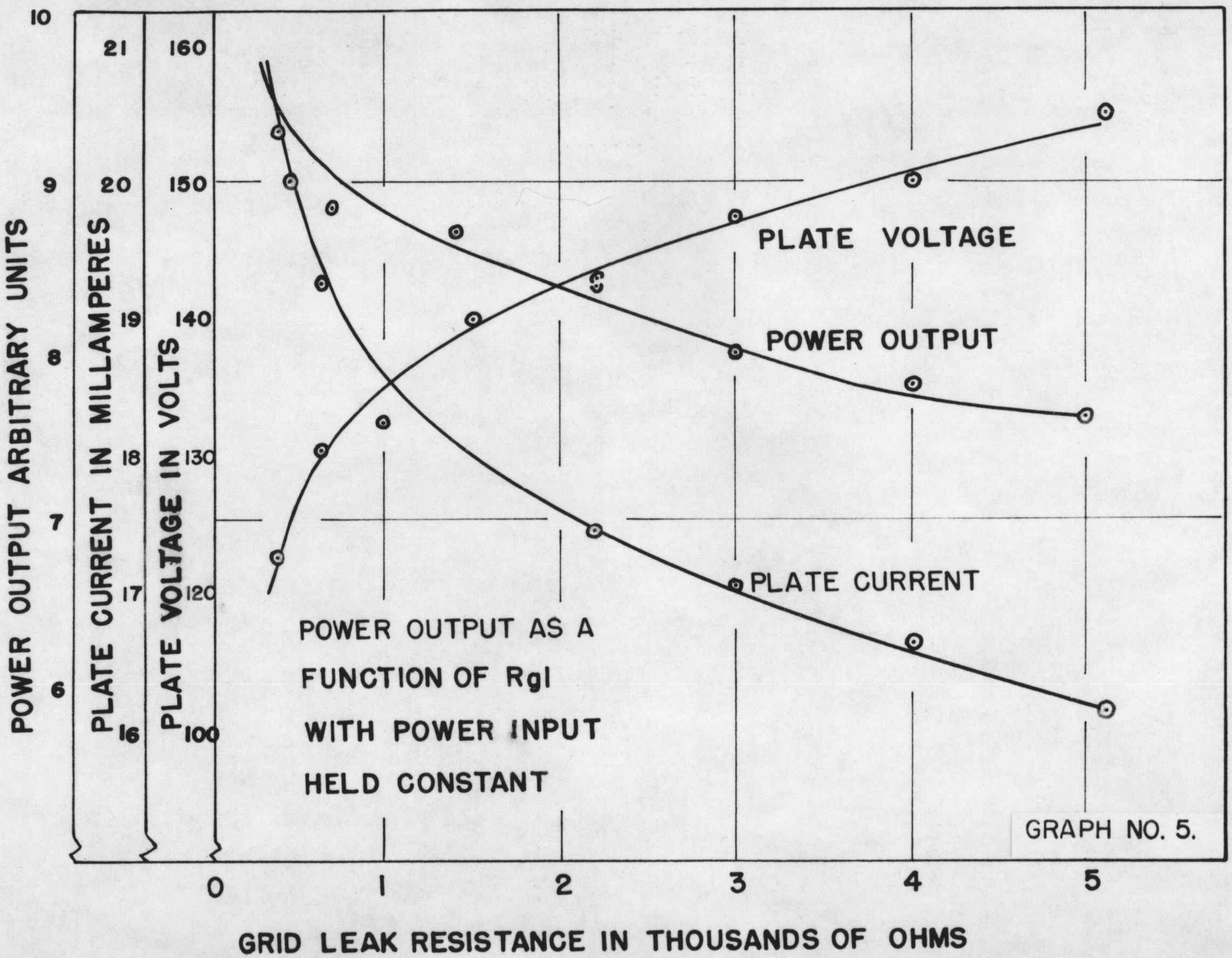
While taking these data it was noticed that when the loop was quite short, oscillations existed at very high frequencies. These parasitic oscillations were caused by the short loop acting as a resonant element instead of a coupling control.

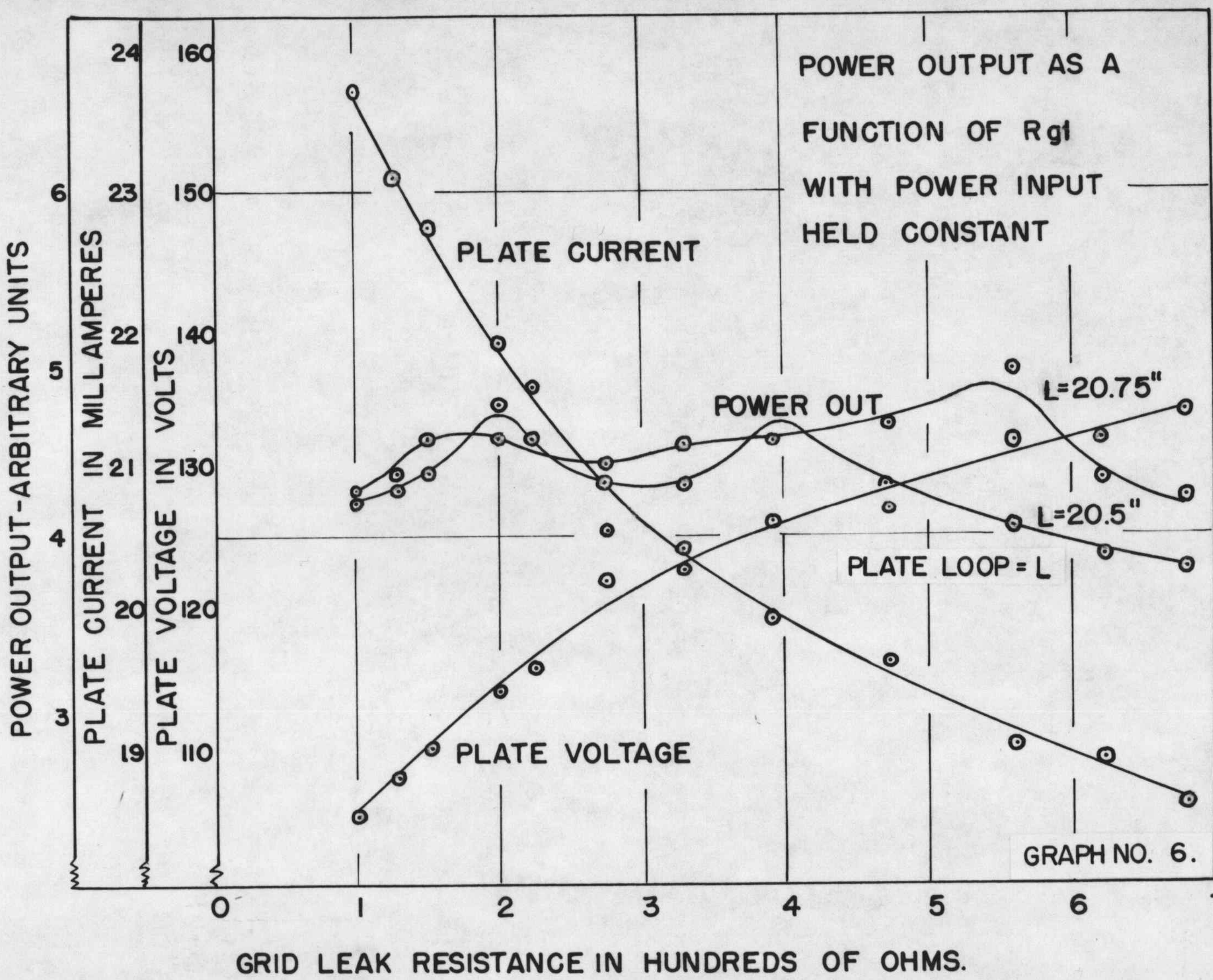
From the first four graphs it is seen that the grid bias and driving voltage are not optimum. Graphs 5 and 6 are for values of R_{gl} smaller than used previously.

At this point it was realized that the 2C40 tube chosen for this model is not capable of delivering enough power to the circuit to give satisfactory results. The losses in the circuit appear to be dissipating a considerable percentage of the generated power which makes it difficult to evaluate the characteristics. If a more powerful tube had been chosen, measuring instruments and stray capacitance changes would have had a much smaller effect on the operation.

This effect becomes much more evident later on when the voltage between the dees is measured. Then it will be seen that with special efforts to keep the impedance of the voltmeter very high to minimize loading, even the smallest load will make measurements unsatisfactory.

Graph 7 shows frequency of oscillation and I_o as functions of plate loop length, L. Referring to graph 7 we see that a 32 percent change in plate coupling loop length gave a 70 percent change in I_o and a 2 percent change in frequency.

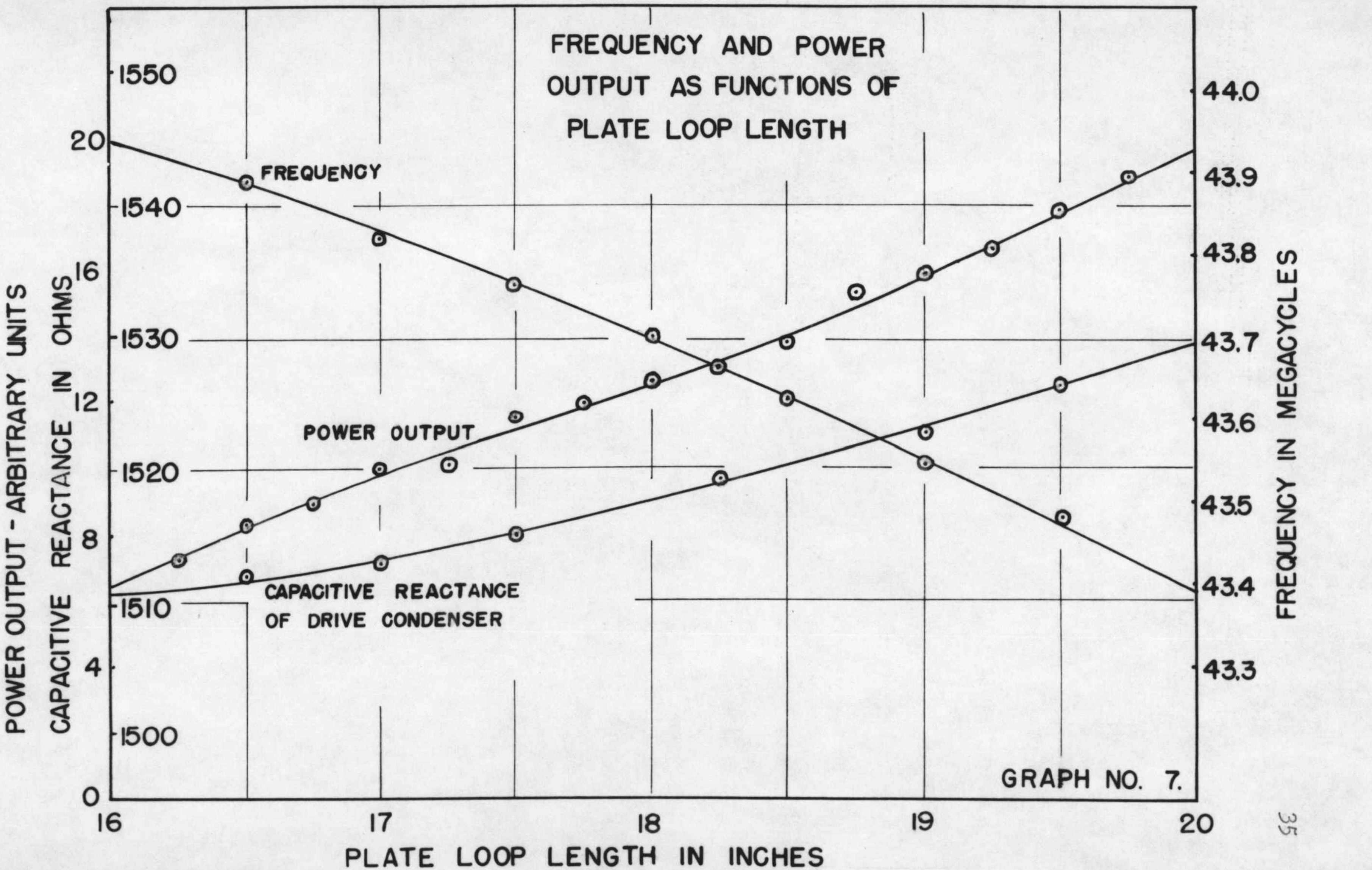

POWER OUTPUT ARBITRARY UNITS
PLATE CURRENT IN MILLAMPERES
PLATE VOLTAGE IN VOLTS
10
21 160
9 20 150
19 140
8
18 130
7
17 120
6
16 100
0
1
2
3
4
5
PLATE VOLTAGE
POWER OUTPUT
PLATE CURRENT
POWER OUTPUT AS A
FUNCTION OF Rgl
WITH POWER INPUT
HELD CONSTANT
GRID LEAK RESISTANCE IN THOUSANDS OF OHMS
GRAPH NO. 5.

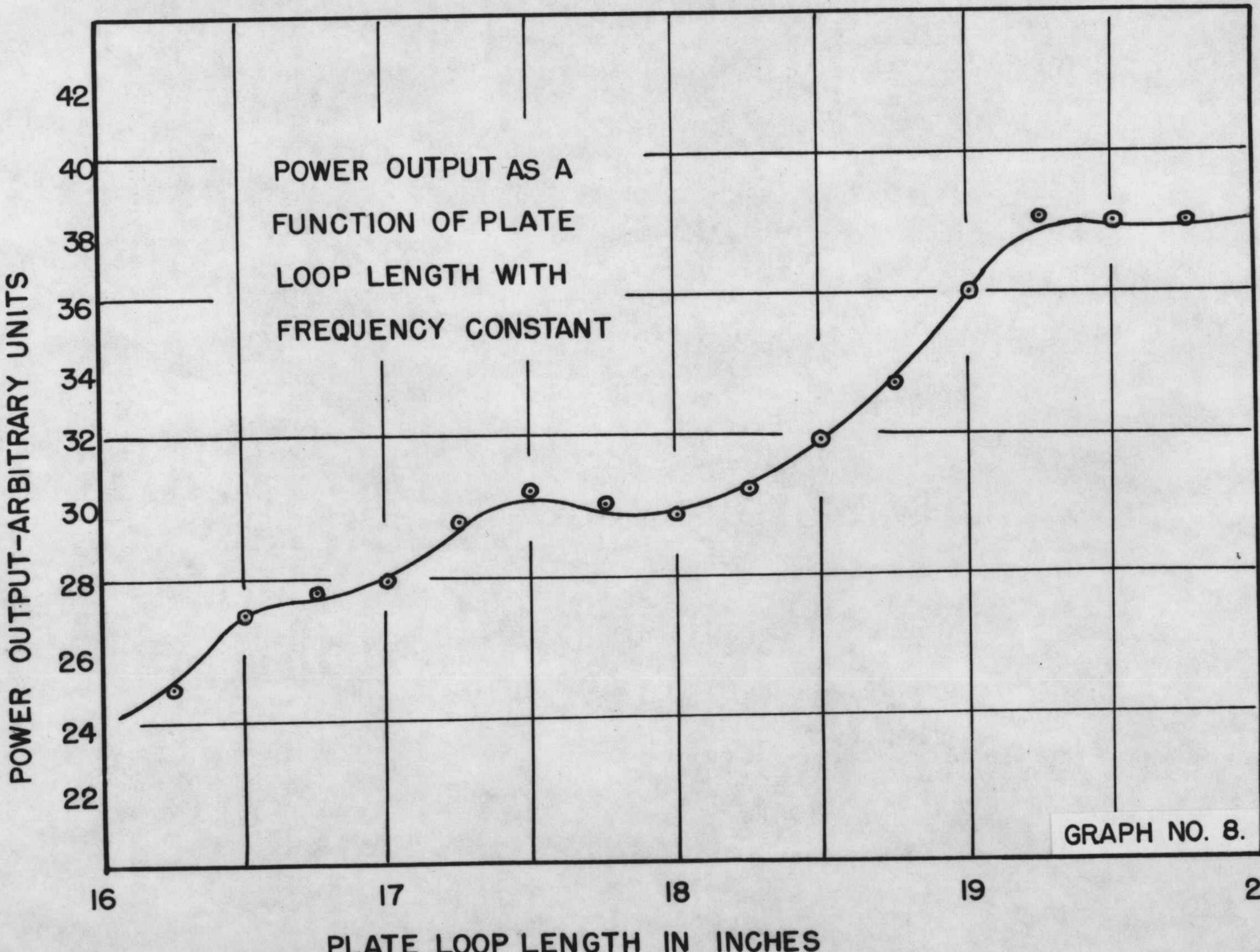

POWER OUTPUT AS A
FUNCTION OF Rg1
WITH POWER INPUT
HELD CONSTANT
PLATE CURRENT
POWER OUT
L=20.75"
L=20.5"
PLATE LOOP = L
PLATE VOLTAGE
GRAPH NO. 6.
POWER OUTPUT-ARBITRARY UNITS
PLATE CURRENT IN MILLAMPERES
PLATE VOLTAGE IN VOLTS
GRID LEAK RESISTANCE IN HUNDREDS OF OHMS.

Data similar to graph 7 were taken for several different values of R_{g1}. The data are not included but it was found that the value of R_{g1} has negligable effect on frequency and I_o for the various values used.

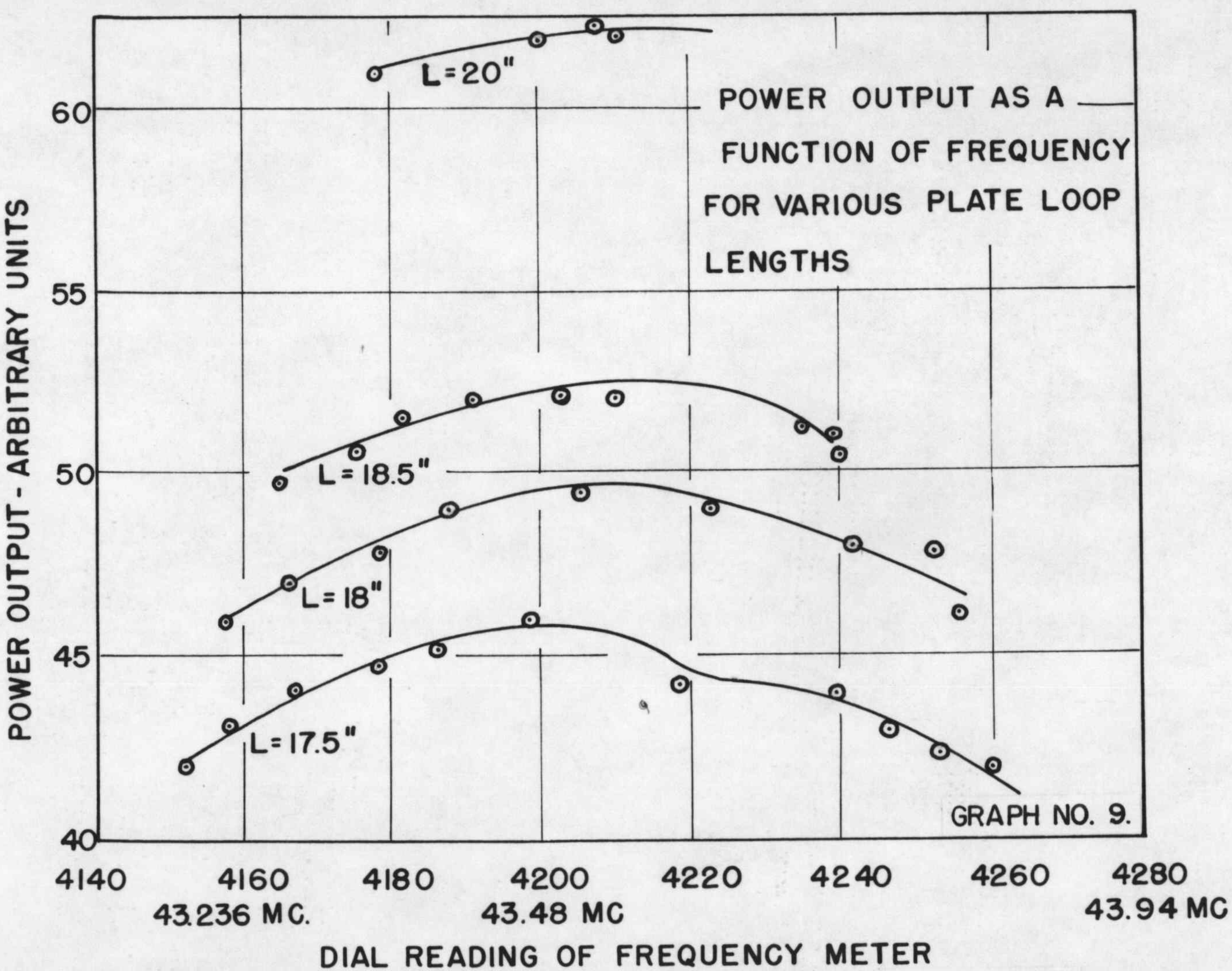
The frequency change with change in plate loop length was reduced to zero by tuning so that power output as a function of loop length could be studied. Graph 8 shows a 40% change in power output with a 32% change in loop length. The slope of this curve may change with frequency as may be seen in graph 9.

Graph 9 shows that I_o is maximum at nearly a constant frequency for various lengths of plate loop. The length of the loop was set and I_o recorded at different frequencies. It is seen that I_o increased and then decreased for each increase of loop length and was maximum at nearly the same frequency for each curve. This clearly illustrates the function of the plate coupling loop as an impedance matching device between the tube and the resonant quarter wave line.


FREQUENCY AND POWER OUTPUT AS FUNCTIONS OF PLATE LOOP LENGTH
FREQUENCY
POWER OUTPUT
CAPACITIVE REACTANCE OF DRIVE CONDENSER
POWER OUTPUT - ARBITRARY UNITS
CAPACITIVE REACTANCE IN OHMS
FREQUENCY IN MEGACYCLES
PLATE LOOP LENGTH IN INCHES
GRAPH NO. 7.
0
4
8
12
16
20
1500
1510
1520
1530
1540
1550
43.3
43.4
43.5
43.6
43.7
43.8
43.9
44.0
16
17
18
19
20


POWER OUTPUT AS A FUNCTION OF PLATE LOOP LENGTH WITH FREQUENCY CONSTANT
POWER OUTPUT-ARBITRARY UNITS
42
40
38
36
34
32
30
28
26
24
22
16
17
18
19
20
PLATE LOOP LENGTH IN INCHES

GRAPH NO. 8.


POWER OUTPUT AS A FUNCTION OF FREQUENCY FOR VARIOUS PLATE LOOP LENGTHS
L=20"
L=18.5"
L=18"
L=17.5"
GRAPH NO. 9.
POWER OUTPUT - ARBITRARY UNITS
40
45
50
55
60
4140
4160
4180
4200
4220
4240
4260
4280
43.236 MC.
43.48 MC
43.94 MC
DIAL READING OF FREQUENCY METER

THE SHIELDED OSCILLATOR

The foregoing data and curves were taken with the 64 inch unshielded oscillator, and while giving general information concerning the oscillator, the shielded unit is of primary concern. With these data as guides for further investigation, the dee stem length necessary for resonance with various dee configurations and the various electronic characteristics needed for successful system control were investigated on the shielded model.

For the next group of data the value of grid leak resistance, R_{gl}, was 390 ohms and with the exception of the last few pages, the direct current plate supply potential was held at plus 110 volts. The power input was allowed to assume an uncontrolled value dependent only on system requirements or loading.

Dees used.

The length of dee stem equivalent to the inductance necessary to resonate with the dee to dee capacitance at the operating frequency will be different for different configurations of the dees. Four sets of dees were constructed so that data could be taken to determine the type of dee required for certain lengths of dee stem. Figures 7 through 11 show sketches of these dees. The calculations of the dee to dee capacitance follow.

$$C = 0.224 \frac{K A}{d} (n - 1) \mu\mu\text{fd}$$

where

A = area of one side of one plate in square inches.

VARIOUS DEE CONFIGURATIONS

NO. 1

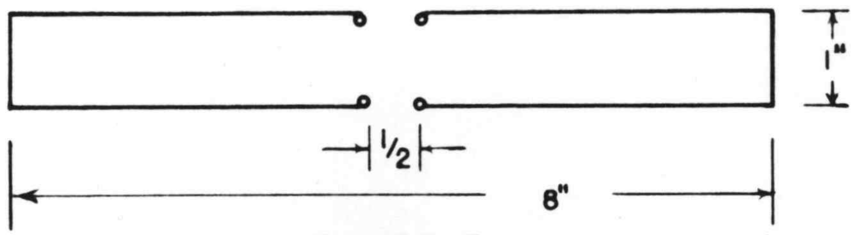


FIGURE 7

NO. 2

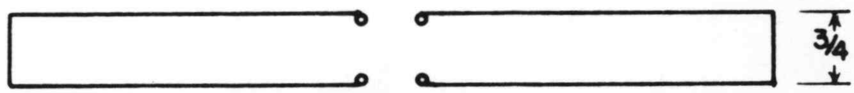
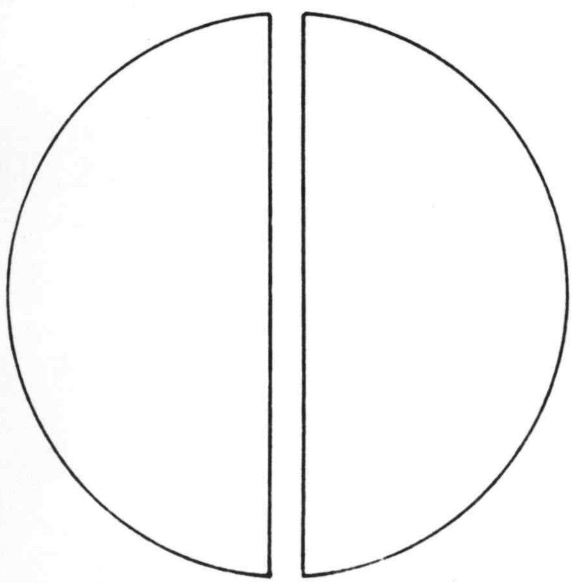
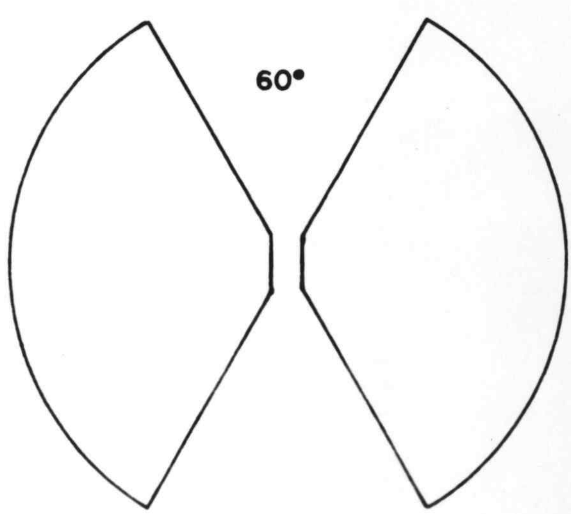


FIGURE 8

NOS. 3&4

FIGURE 9





NOS. 1, 2 AND 3

FIGURE 10

NO. 4

FIGURE 11

d = spacing between plates in inches

K = dielectric constant = 1.0

n = number of plates = 3.

Three things are not accounted for in the calculations of dee capacitance. They are: (1) the missing 1/2 inch strip between the dees, (2) the vertical edges of the dees and the capacitance they have with the chamber, and (3) the presence of the stems in close proximity to the dees and chamber. These three effects are considered small in comparison to the size of the dees.

Sample calculation: Dee 1 for the 1/4 scale model.

Total capacitance:

$$C_t = (0.224)\,\frac{50.3}{0.125}\,(2) = 180.2\ \mu\mu\text{fd.}$$

Capacitance per dee to ground:

$$C = 90.1\ \mu\mu\text{fd.}$$

Capacitance through ground (C load on lines):

$$C = 45.05\ \mu\mu\text{fd.}$$

TABULATION DEE TO DEE CAPACITANCE

Table II

Dee No.	1/4 Model	Full Scale
Dee 1	45.05 μμfd	180 μμfd
Dee 2	22.5 μμfd	90 μμfd
Dee 3	12.425 μμfd	49.7 μμfd
Dee 4	8.7 μμfd	34.76 μμfd

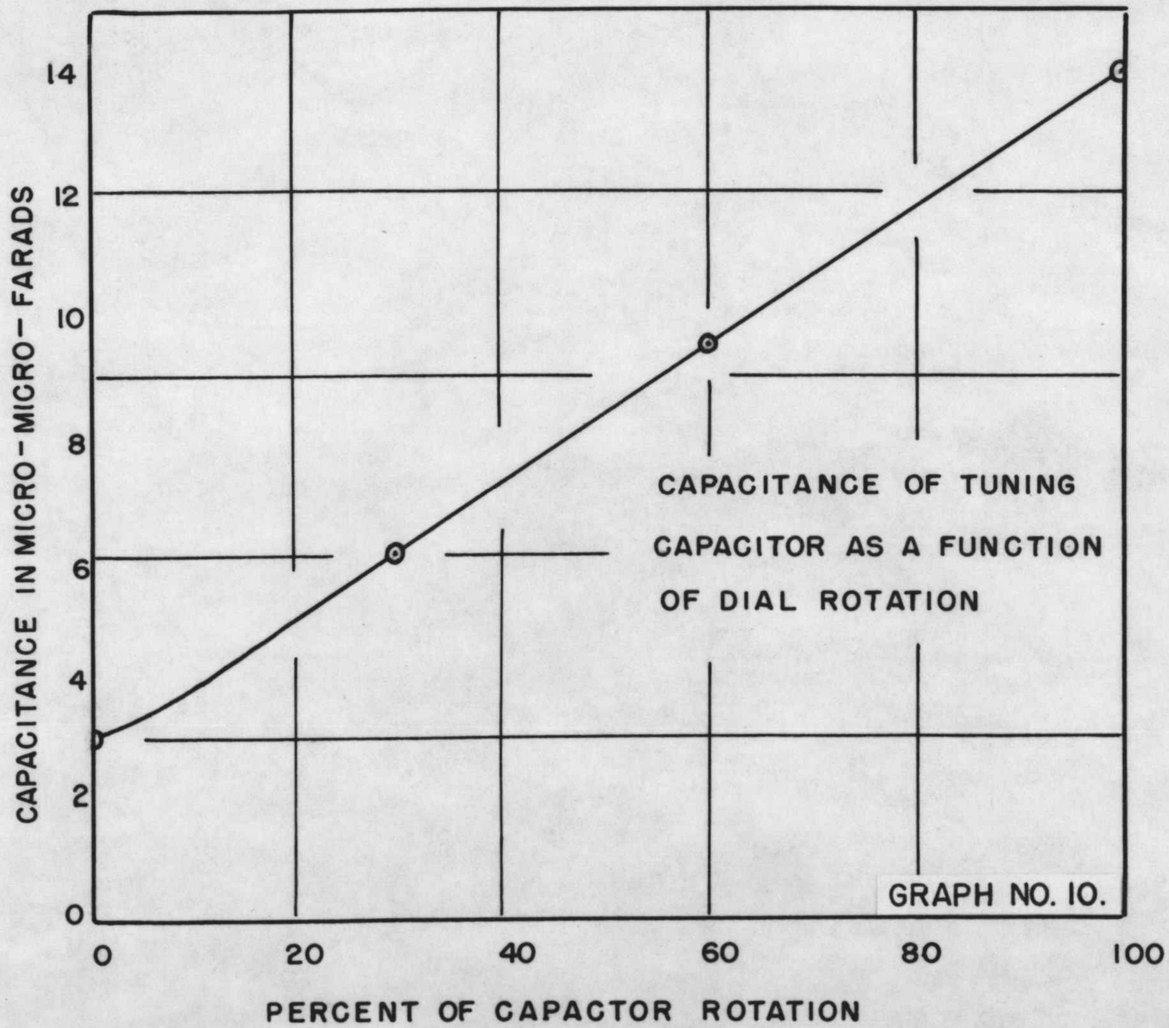
The first operation of the shielded model was with dees number 1. No tabulated data will be presented for these dees because the dee to dee capacitance was entirely too high for satisfactory operation. A dee stem length of 32 inches (a full scale length of 10.67 feet) gave a frequency of approximately 33.9 megacycles (a full scale frequency of 8.47 megacycles). A dee stem length of 28 inches (a full scale length of 9.33 feet) gave a frequency of approximately 38.0 megacycles (a full scale frequency of 9.5 megacycles). Both of these frequencies are too low and thus dees number 1 were removed rather than shorten the stems any more.

Dees number 2 have half the capacitance of the number 1 dees. With the tuning capacitance dial set between 10 and 15, a dee stem length of 36 inches (a full scale length of 12 feet) gave a frequency of 43 megacycles (a full scale frequency of 10.75 megacycles). The data for various operating characteristics were therefore taken with this set of dees.

Tuning Capacitance.

The effect of the tuning capacitance on frequency when dees number 2 were used is shown in graph number 12. The tuning dial had 100 divisions for a 180° rotation, representing a change in tuning capacitance from 3.0 $\mu\mu$fd's to 14 $\mu\mu$fd's (12 to 56 $\mu\mu$fd's full scale). The capacitor was rated at a maximum of 30 $\mu\mu$fd's per section; the plotted capacitance is the series value as measured on a General Radio 605A audio frequency impedance bridge.

Selection of the optimum value of driving capacitance for best


CAPACITANCE IN MICRO-MICRO-FARADS
0
2
4
6
8
10
12
14
0
20
40
60
80
100
PERCENT OF CAPACTOR ROTATION
CAPACITANCE OF TUNING CAPACITOR AS A FUNCTION OF DIAL ROTATION
GRAPH NO. 10.

operation, while keeping the frequency constant, is important because the combination of driving voltage and grid bias determines the angle of plate current flow and therefore the operating efficiency. Graph number 11 shows the power input and power output as functions of plate coupling loop length for three values of driving capacitance. The driving voltage is expected (though not measured) to increase with decreasing values of C. The results show maximum power output for a capacitance of 240 μμfd. At 43 megacycles, the reactance of this capacitance is 1543 ohms.

For the full scale oscillator, a 1543 ohm reactance would correspond to a capacitance of 960 μμfd at a frequency of 10.8 megacycles, which would probably be very much too large a reactance for satisfactory operation. This discrepancy is caused by the fact that while the oscillator upon which these experiments have been performed is a scale model of the proposed large oscillator, the 2C40 tube is not homologous to the RCA 5770. It is assumed that a value much less than 1500 ohms would give sufficient drive for full rated beam current because the RCA 5770 is capable of handling many times the power required by the copper losses and cyclotron beam load.

Loading.

This oscillator has the feature of ceasing oscillations when heavily overloaded. An investigation of power input as a function of power output, or loading, shows in graph number 13 that the plate current is reduced (plate supply voltage held constant) when the load increases heavily. This is due to a loss in drive voltage resulting from a

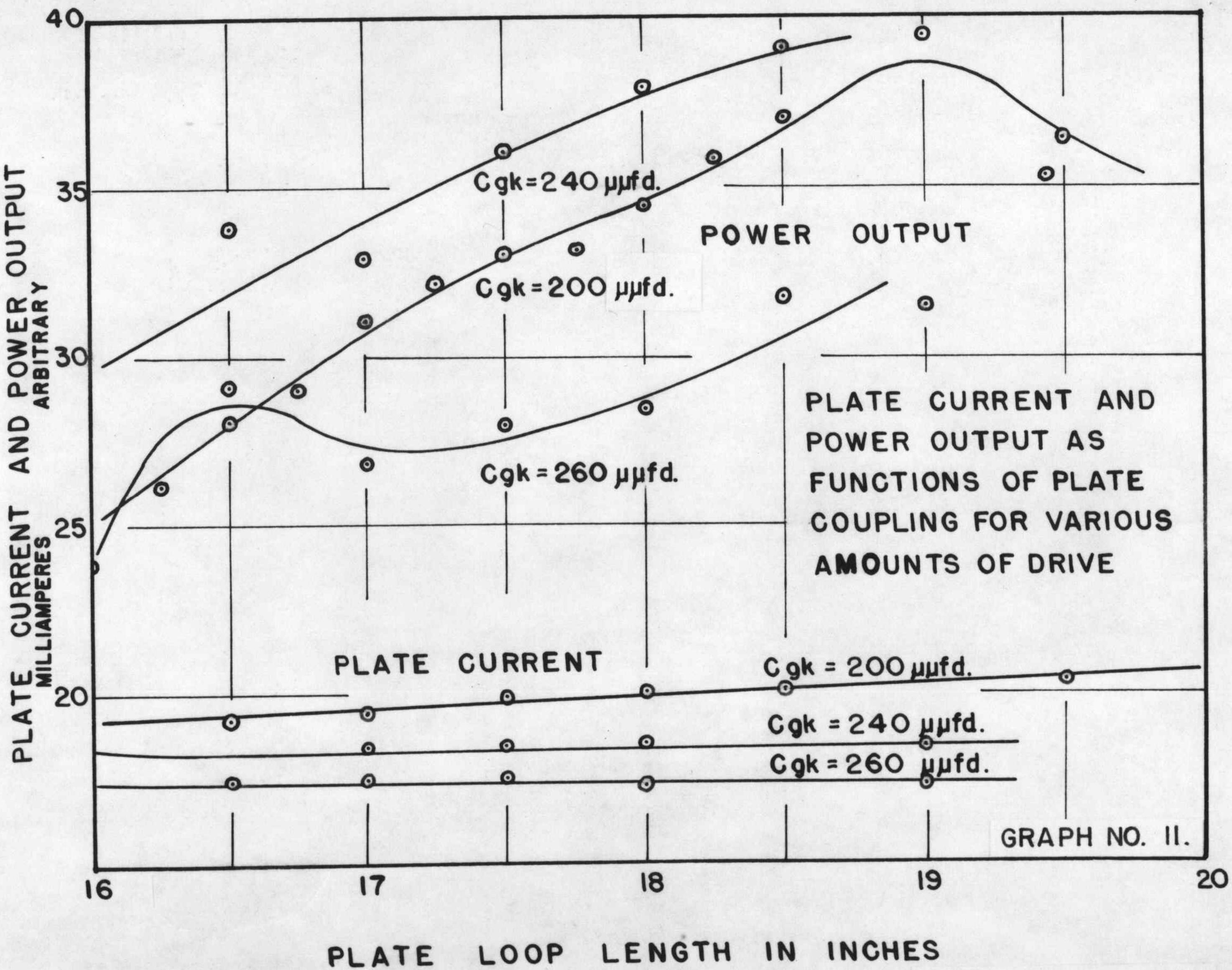


PLATE CURRENT AND POWER OUTPUT
MILLIAMPERES
ARBITRARY
40
35
30
25
20
16
17
18
19
20
PLATE LOOP LENGTH IN INCHES
Cgk = 240 μμfd.
Cgk = 200 μμfd.
Cgk = 260 μμfd.
POWER OUTPUT
PLATE CURRENT AND POWER OUTPUT AS FUNCTIONS OF PLATE COUPLING FOR VARIOUS AMOUNTS OF DRIVE
PLATE CURRENT
Cgk = 200 μμfd.
Cgk = 240 μμfd.
Cgk = 260 μμfd.
GRAPH NO. 11.

44

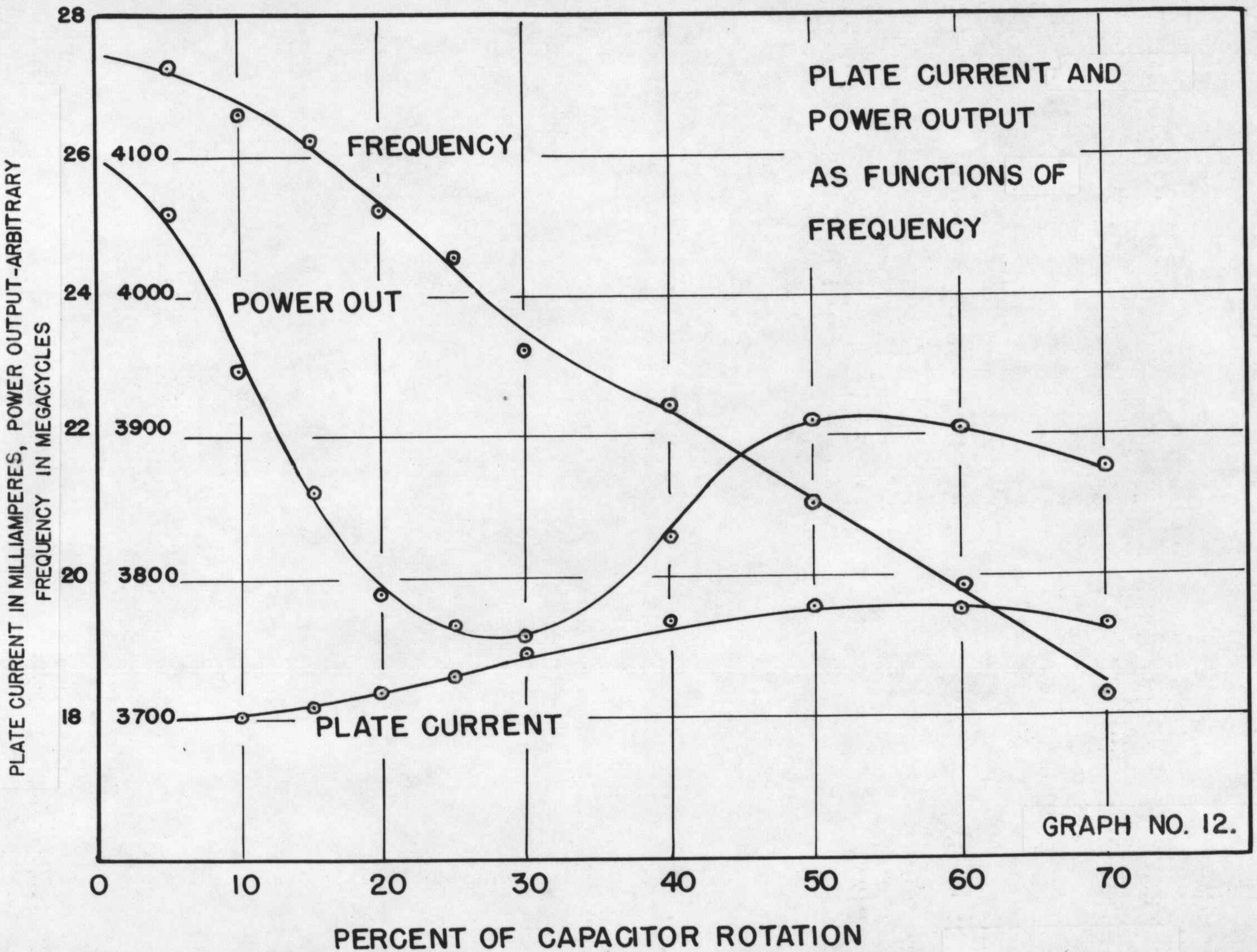
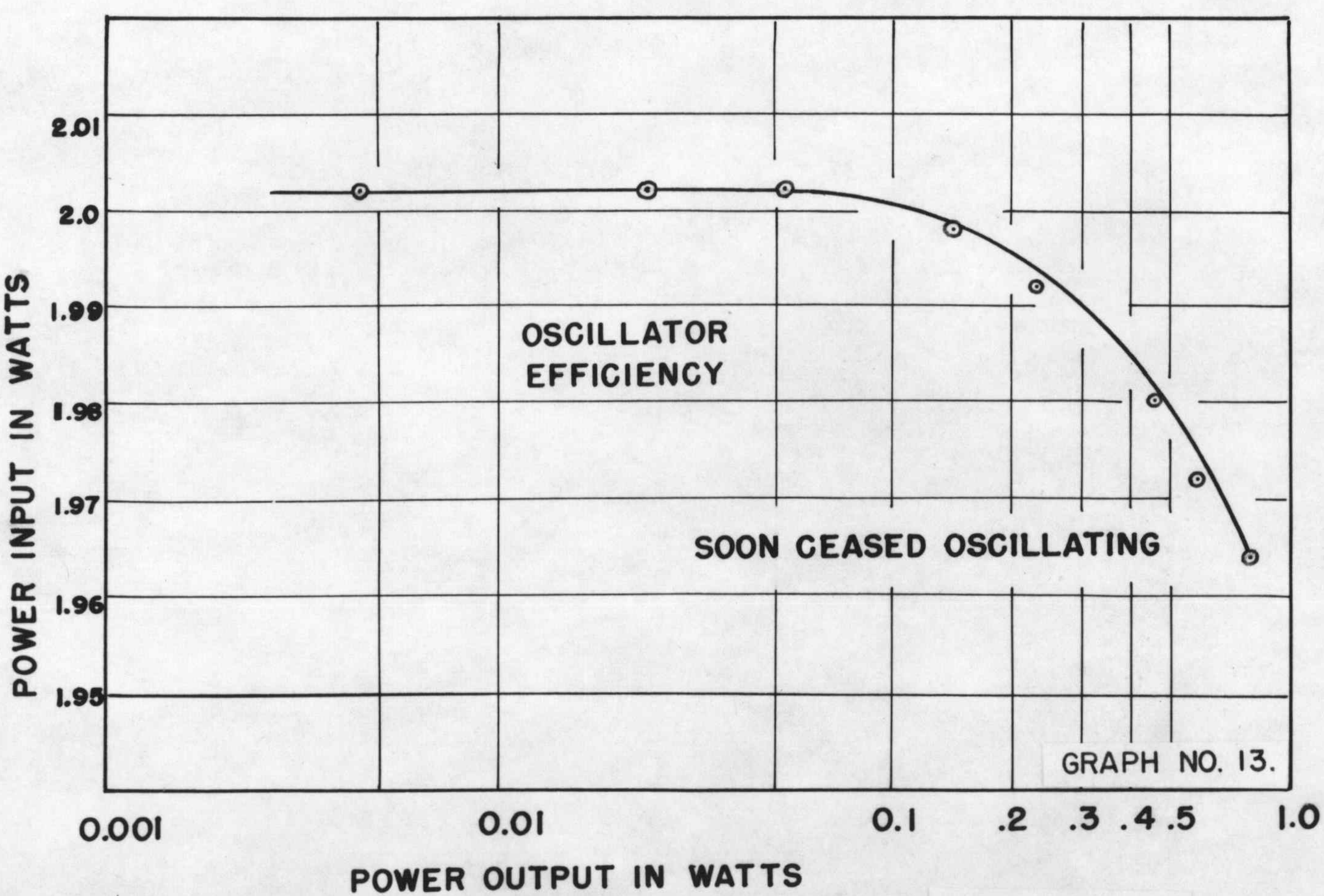


PLATE CURRENT AND POWER OUTPUT AS FUNCTIONS OF FREQUENCY
FREQUENCY
POWER OUT
PLATE CURRENT
GRAPH NO. 12.
PLATE CURRENT IN MILLIAMPERES, POWER OUTPUT-ARBITRARY
FREQUENCY IN MEGACYCLES
28
26
24
22
20
18
4100
4000
3900
3800
3700
0
10
20
30
40
50
60
70
PERCENT OF CAPACITOR ROTATION


OSCILLATOR
EFFICIENCY
SOON CEASED OSCILLATING
GRAPH NO. 13.
POWER INPUT IN WATTS
2.01
2.0
1.99
1.98
1.97
1.96
1.95
0.001
0.01
0.1
.2
.3
.4
.5
1.0
POWER OUTPUT IN WATTS

decrease in radio frequency tank circuit current when the increase in loading causes the effective resistance to increase at the point in the circuit where the drive voltage is developed.

The magnitude of power output is not known but by considering the value of I_o and the resistive impedance of the current recording instrument, it is estimated that the power dissipated in the load was slightly more than one watt for two watts input at the upper end of the curve.

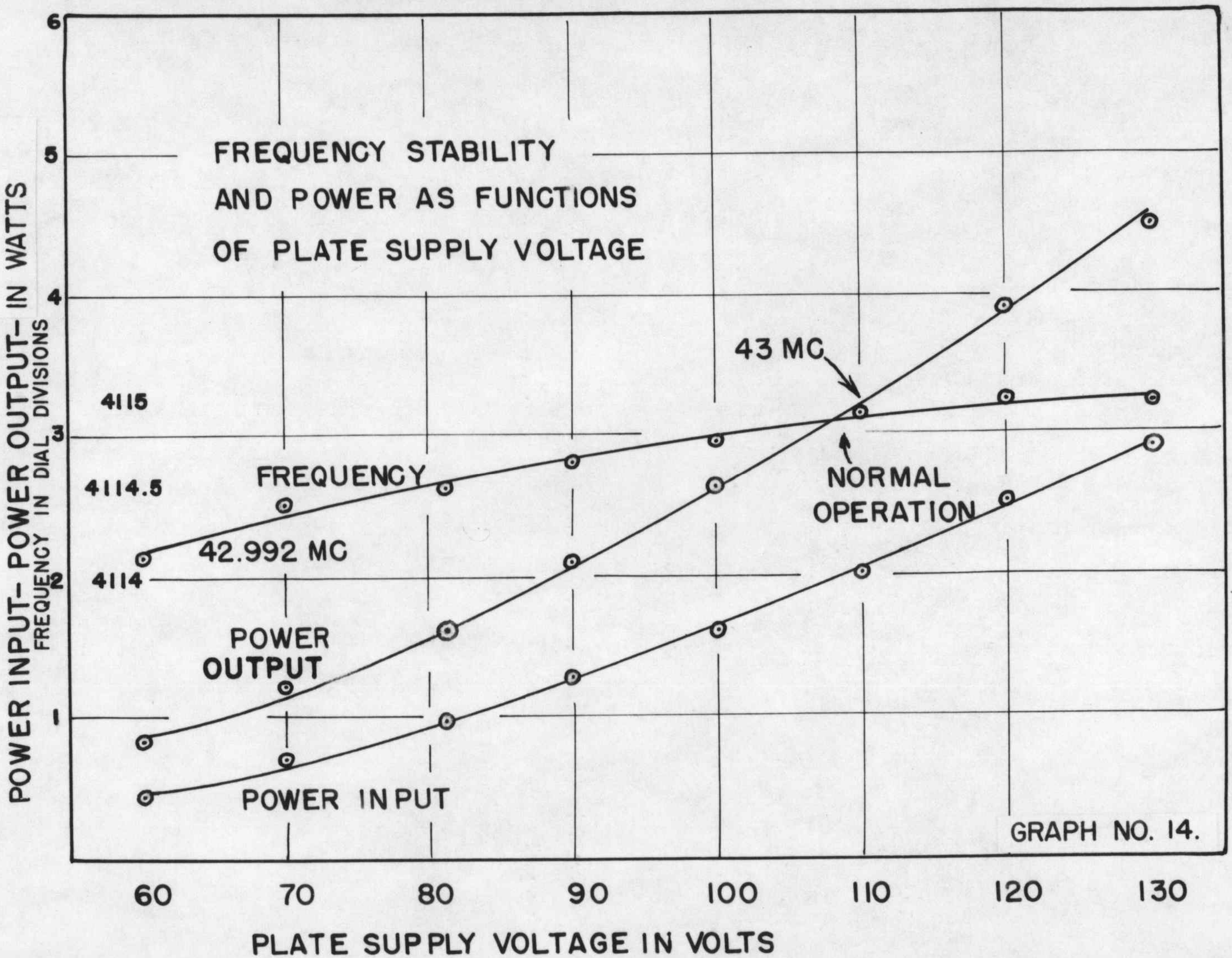
Frequency Stability.

Frequency stability as a function of plate supply potential was investigated for a 2 to 1 range of plate supply voltage. The oscillator was tuned to 43 megacycles with a plate voltage of 110 volts and the load coupled lightly so that power input and output could be measured. By varying the plate supply from 60 volts to 120 volts, the frequency varied from 42.991 megacycles to 43.102 megacycles, a change of 0.111 megacycles, which represents a change of approximately 2581 parts per million. A 2 to 1 change in plate supply voltage caused a 5.36 to 1 change in power input and a 4.52 to 1 change in power output.

Frequency stability as a function of cathode emission or temperature was not studied.

Dee Voltage.

An attempt to measure the dee to dee voltage along the length of the inner edges of the dees was not successful because the power required to operate the voltmeter was such as to excessively load the oscillator. This caused the voltage between the dees to become a function of the impedance of the resonant system. The voltmeter impedance in parallel with the oscillator tank impedance lowered the tank impedance a different amount at each position along the dee edge because each position was a different number of electrical degrees from the ends of the dees. These measurements could have given satisfactory data by use of an oscillator tube capable of much greater power thus reducing the effect of a changed tank circuit impedance on the drive of the oscillator to a negligable value. It is believed that a larger tube would require a smaller C_{gk} drive capacitance which would result in a lower impedance source of drive voltage.


FREQUENCY STABILITY
AND POWER AS FUNCTIONS
OF PLATE SUPPLY VOLTAGE
POWER INPUT- POWER OUTPUT- IN WATTS
FREQUENCY IN DIAL DIVISIONS
6
5
4
3
2
1
4115
4114.5
4114
43 MC
FREQUENCY
42.992 MC
NORMAL
OPERATION
POWER
OUTPUT
POWER INPUT
GRAPH NO. 14.
60
70
80
90
100
110
120
130
PLATE SUPPLY VOLTAGE IN VOLTS

CALCULATION OF OPTIMUM CHARACTERISTIC AND RESONANT IMPEDANCES

The foregoing data and discussions are of value in understanding a self excited oscillator used as the voltage generator for a cyclotron and give foresight for future investigations. Optimum values of both characteristic impedance and resonant impedance of the lines can also be calculated.

An approximate value of Z_o to be used for calculating the performance of this oscillator can be obtained by neglecting the effect of the plate coupling loop and solving the equations for the characteristic impedance of a shielded two-wire transmission line. One can also determine whether Z_o should be increased or decreased, and approximately how much, to effect an improvement in operation. The following discussion is based on an accelerating system designed for maximum resonant impedance between the dees rather than maximum Q. This choice is made so that the dee to dee voltage will be maximum, even when the system is loaded. Another reason is that with a Q other than maximum which means an oscillator efficiency less than maximum, the use of the RCA 5770 oscillator tube makes this unimportant.

We know that for resonance of short-shorted parallel stubs (2, pp. 188-189)

$$\omega C Z_o = \operatorname{Cot} \theta \qquad (11)$$

where ω = $2\pi f$, the angular velocity

f = resonant frequency in cycles per second

Z_o = characteristic impedance in ohms

C = loading capacitance on end of stubs to produce resonance

θ = electrical length of stubs in degrees.

From the same reference,

$$r = \frac{Z_o}{K}\left(\frac{1-\cos 2\theta}{2 + \sin\theta}\right) \qquad (12)$$

where r = resonant impedance of the open end of the line

$K = R_o / 2\omega L_o$

R_o = line resistance per unit length

L_o = line inductance per unit length.

Combining equations (11) and (12)

$$\frac{r}{d\sqrt{F}} = \frac{100X_c^2}{10^{(X_c / 276 \tan\theta)}} \cdot \phi(\theta) \qquad (13)$$

where d = center-to-center spacing in centimeters

F = frequency in hundreds of megacycles per second

$$\phi(\theta) = 0.458\ \frac{1 + \cos 2\theta}{2\theta + \sin 2\theta}\ . \qquad (14)$$

These equations are plotted in Figures 12 and 13.

Solving for Z_o (3, pp.327),

$$Z_o = \frac{276}{\sqrt{\epsilon}}\left\{\log_{10}\left[\frac{4h \tanh \frac{\pi D}{2h}}{\pi D}\right] - \sum_{m=1} \log_{10}\left[\frac{1 + U_m^2}{1 - V_m^2}\right]\right\} \qquad (15)$$

for $d \ll D, W, h$, where

$$U_m = \frac{\operatorname{Sinh} \frac{\pi d}{2h}}{\operatorname{Cosh} \frac{m\pi W}{2h}}\ ; \quad V_m = \frac{\operatorname{Sinh} \frac{\pi D}{2h}}{\operatorname{Sinh} \frac{m\pi W}{2h}}$$

Line dimensions (full scale)

$$d = 6.5'', \quad D = 19.5'', \quad W = 39'', \quad h = 19.5''$$

where on Figure 2, A, B, C and D are now W, h, D and d respectively, so that

$$\frac{\pi W}{2h} = \frac{\pi\,(39)}{(39)} = \pi$$

and

$$\frac{m\pi W}{2h} = m\pi$$

The solution of equation (15) gives

$$Z_o = 138.2 \text{ ohms}$$

To obtain θ, the length of the resonant system in electrical degrees, the following tabulation of data with dees numbers 2, 3 and 4 respectively gives L, the total line length. This length, L, includes the dees but there is some question as to where the actual electrical end of the stubs occurs. The overall length is used, knowing it to be a close approximation, because the length of the dees does have an effect on the line length as well as the load capacitance. The equation for θ is

$$\theta = \frac{360\,L}{\lambda}. \tag{16}$$

TABULATION OF OSCILLATOR CHARACTERISTICS, STUBS PLUS DEES

TABLE III

Dee No.	Model Frequency	Model Length	Full Scale Length	Electrical Length
1	33.9 mc	32"		
1	38.0 mc	28"		
2	43 mc	36"	12'	47.2°
3	43 mc	39"	13'	51.2°
4	43 mc	41.5"	13.75'	54.4°
4	68.5 mc	23"	7.66'	42.8°
4	76 mc	19"	6.34'	44°

The following calculations are necessary for use of Figures 12 and 13. These figures were taken directly from reference 2. Figure 12 is a graph of the resonant impedance of a shorted twin-line stub, giving solutions to equation (13) when the electrical length of the stubs and the reactance of the loading capacitance are known. For resonance

$$Z_o = X_c / \tan \theta \tag{17}$$

or

$$X_c = Z_o \tan \theta \; . \tag{18}$$

The characteristic impedance of the dee stems investigated was calculated previously and various values of the electrical length may be taken from Table III.

Example: Choice of dees number 2 at a frequency of 43 megacycles per second gave a θ of 47.2°

$$X_c = (138.2)(\tan 47.2^\circ)$$

$$= 149 \text{ ohms.}$$

Entering Figure 12, we obtain a value for

$$\frac{r}{d\sqrt{F}} = 85{,}000 \text{ ohms}$$

or

$r = 689{,}400$ ohms which is the resonant impedance between the dees. However, with an X_c of 149 ohms, Figure 12 shows it is possible to obtain a maximum value of $\frac{r}{d\sqrt{F}}$ of 120,000 ohms

or $r = 973{,}200$ ohms, which would require a different value of θ. It is seen in equation (17) that we may have a different θ at resonance by changing the value of Z_o. Z_o may be calculated from equation (17) or found by use of Figure 13. In this example we need a

$$Z_o = 170 \text{ ohms}$$

for an optimum line, resonant at 43 megacycles with an effective dee to dee capacitance of 24.82 micro-micro farads.

The solution of Z_o gave a value of 138.2 ohms which is very doubtful for case IV because the length of the stubs minus the dees was only one-half of the total stem-plus-dee length. This is also evident in the solution for C in case IV. It is higher than any other case which we know cannot be correct.

From table IV, it is seen that for all cases a higher Z_o than that used is indicated for optimum resonant impedance. Here again the values listed are approximations but can be used for intuitive thinking about how to change the line dimensions. Z_o (138.2 ohms) is more apt to be a good approximation using the greatest length case because the dees represent the smallest portion of the electrical length. The presence of the plate coupling loop between the stems will have the effect of a small capacitance in parallel with the dees, and will lower the actual Z_o of the stems by effectively bringing them closer together. This shows that if we need an optimum Z_o higher than the calculated Z_o, a greater need for changing the stem Z_o exists than if the needed optimum value were lower than Z_o calculated.

Case II indicates a need for a 26.4% increase in Z_o for optimum resonant impedance. It is believed that such an increase would be too much if constructed into a model and tested but no guess is offered as to how much Z_o should be increased.

Equation (11) shows that for constant ω and C, an increase in Z_o will cause an increase in θ for resonance. According to Table III this is not desirable because with the present value of Z_o, an impractical stem length is necessary for proton frequency operation. For the same reason operation at the deuteron frequency would require special stem construction. Therefore the dee to dee capacitance must be kept low.

The only explanation offered for the dips in the curves of Graphs 6, 8, 11, and 12 is that stable operation was not always possible. Great effort was taken to minimize movement of influencing objects in the room during operating periods but some undesirable influence was unavoidable.

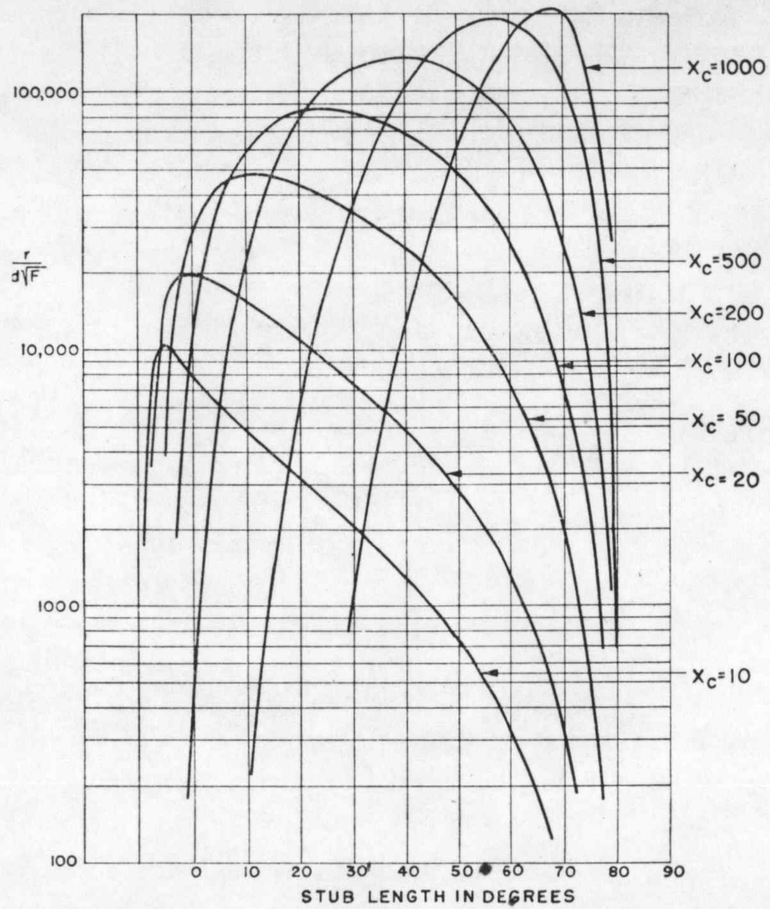


FIG.12—Resonant impedance of a shorted twin-line stub. For resonance, $Zo = X_c/\tan\theta$
d = Spacing in cm
F = Frequency in hundreds of mc
r = Resonant impedance in ohms
X_c = Lumped capacitive reactance at open end

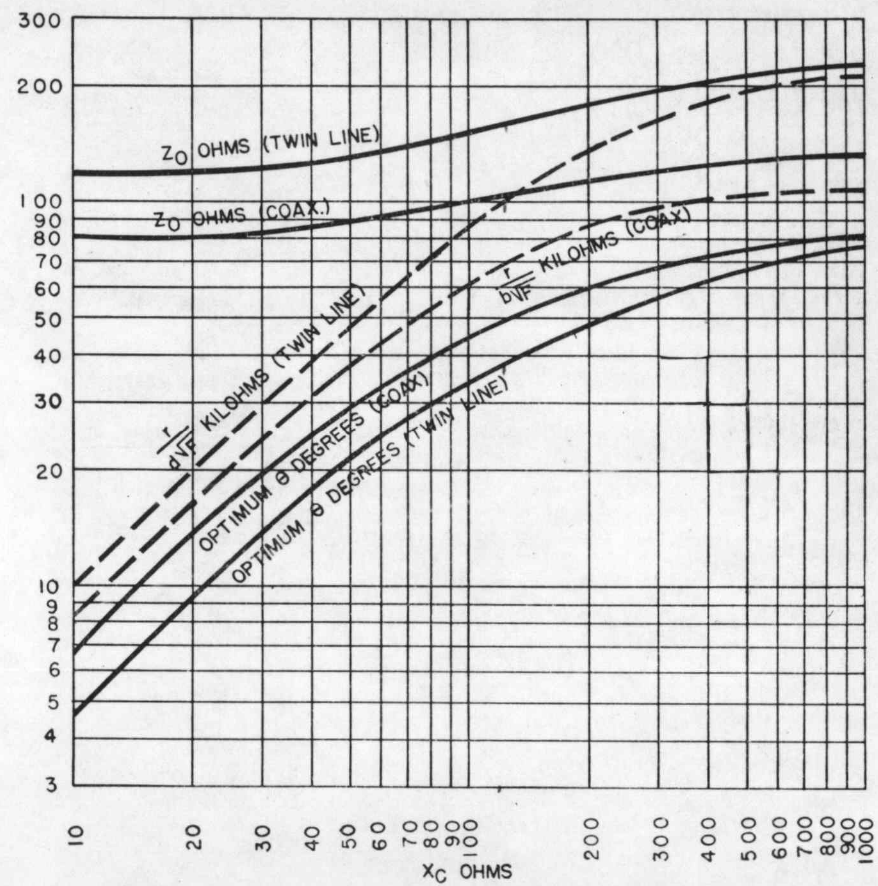


FIG. 13—Parameters and performance of the optimum line as a function of X_c.

TABLE IV

			Line Length			Loading Capacitance		Resonant Imp		Z_o	
CASE	DEE	FREQ	INCHES	DEGREES	OPTIMUM	X_c	C	ACTUAL	OPTIMUM	ACTUAL	OPTIMUM
I	2	43mc	36"	47.2°	42°	149 ohms	24.8 μμfd	6.9 meg	9.76 meg	138.2 ohms	170 ohms
II	3	43mc	39"	51.2°	46°	171.8ohms	22.55 μμfd	7.72 meg	10.02 meg	138.2 ohms	175 ohms
III	4	43mc	41.5"	54.4°	48°	194 ohms	19.2 μμfd	8.13 meg	10.06 meg	138.2 ohms	180 ohms
IV	4	76mc	23"	44°	40°	133.4ohms	27.8 μμfd doubtful	6.5 meg	8.54 meg	138.2 ohms	165 ohms

Tabulation of pertinent experimental and calculated data

CONCLUSIONS

From the results obtained the following oscillator specification changes are recommended:

1. Use dees having as low a capacitance as is possible for proper acceleration.
2. If further investigation is to be conducted, a more powerful oscillator tube should be used.
3. The plate coupling loop should be extended to a definite length for optimum operation.
4. A protective overload device should be incorporated in the plate supply to protect the tube in the event of a metallic short on the dees.
5. The characteristic impedance of the line should be increased 20 to 25%.
6. Turn the oscillator on, when starting operation, with full plate voltage applied with a relay switch so that oscillations will build up quickly.
7. Variable vacuum capacitors would be an advantage for tuning the oscillator. If they were used, a frequency discriminating servo system could be constructed as a remote frequency-control vernier.

This form of self-excited oscillator appears in all respects to be as near as possible the ideal type of dee voltage source for constant-frequency continuous-wave cyclotrons. It is simple, rugged and reliable.

It requires a minimum amount of instrumentation, is compact and can be constructed without the cost of an elaborate radio frequency coupling system. The balanced floating radio frequency circuit, fully shielded, should have a minimum of radiation loss resulting in minimum radio frequency interference.

This oscillator could be well adapted to a high-power pulsed frequency-modulated service. Its low impedance source of driving voltage allows a minimum of parasitic elements and by replacing the dee-stem tuning capacitance with a suitable reactance tube it could easily be frequency modulated.

BIBLIOGRAPHY

1. Baker, W.R. The oscillator for the injector cyclotron of the quarter-scale bevatron. Radiation laboratory, Department of physics, University of California, Berkeley, California Report UCRL-457. Sept. 20, 1949.

2. Diamond, Joseph M. Shorted stubs of high resonant impedance. Proceeding of the institute of radio engineers 40: 188-189. 1952.

3. Federal Telephone and Radio Corporation. Reference data for radio engineers. 3d ed. New York, Knickerbocker, 1949 640 p.

4. Terman, Frederick Emmons. Fundamentals of radio. New York, McGraw-Hill, 1938. 458 p.

5. Terman, Frederick Emmons. Radio engineers' handbook. New York, McGraw-Hill, 1943. 1019 p.

6. Zeluff, Vin and John Markus (ed.) Electronics manual for radio engineers. New York, McGraw-Hill, 1949. 879 p.