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Specifications and design of RF power amplifier for proton cavity

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September 1987

Collider Accelerator Department

Brookhaven National Laboratory

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SPECIFICATIONS AND DESIGN OF RF POWER AMPLIFIER FOR PROTON CAVITY

AD

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No. 92

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SEPTEMBER 21, 1987

ACCELERATOR DEVELOPMENT DEPARTMENT

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SPECIFICATIONS AND DESIGN OF
RF POWER AMPLIFIER FOR PROTON CAVITY

M. Meth and Alessandro Ratti

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INTRODUCTION

The power amplifier and cavity system for proton acceleration must be designed to accommodate heavy beam loading and provide a low output resistance to the beam. The large value of required peak RF power dictates that the amplifier operate class B or AB, minimizing the size of the power supplies and reduce cooling requirements. Class B push-pull operation can be implemented by employing either a two-tube driver or a one-tube driver in conjunction with a figure-of-eight loop magnetically coupling the two ferrite stacks within each cavity. This winding provides tight, broad band RF coupling between the two ferrite stacks and causes the cavity to be operated as a 2:1 step-up transformer. This aspect of the system is discussed in Booster Technical Note 84 [1]. A one tube driver was selected, based on the power ratings of available high-voltage tubes and a physical space limitation for the amplifier. The amplifier will be installed in the tunnel adjacent to the cavity.

AMPLIFIER SPECIFICATIONS

Two amplifiers are required to drive two cavities (stations). Each cavity (station) consists of two gaps, with each amplifier driving the two gaps in parallel. The maximum accelerating voltage is 90 kV peak or 22.5 kV per gap. Two voltage modes are contemplated for the system:

First, a full voltage mode with the gap voltage constant at 22.5 kV, over the full accelerating cycle; or

Second, a reduced voltage mode with the gap voltage decreasing from 22.5 kV to 17.5 kV over the accelerating cycle.

The amplifier power requirements was calculated for a beam intensity of 0.75×10^{13} protons per bunch. The injection rf frequency is 2.4 MHz, the maximum rf frequency is 4.2 MHz. The relevant cavity parameters are tabulated in Booster Technical Note 85 [2]. The power requirements for various machine phases are given in Table I. This table also gives the maximum output resistance of the cavity, Robinson resistance.

The power specifications are reduced to required cavity current and is given in Table II for the various machine phases. At the injection phase the beam induces a current that is in quadrature with the cavity voltage detuning the cavity. As the cavity retunes the beam induces a current that is in phase with the cavity voltage.

The tube dissipation is a maximum at the injection phase, characteristic of tuned amplifiers feeding a non-resonant load. The plate current is a maximum at the maximum beam acceleration phase. The plate voltage is determined from the peak swing of 22.5 kV/gap. Since the cavity has a 2:1 turns ratio, the peak plate voltage swing is 11.25 kV. This dictates that the plate supply (E_{bb}) voltage be at least 12.5 kV. A plate supply voltage of 13 kV was selected. A lesser value for E_{bb} can be used if the cavity is tapped for a higher turns ratio. But, the peak current would increase in the same proportion, that the voltage is reduced. Also the impedance increases by a factor equal to the square of the turns ratio.

CROSS COUPLING

The cross coupling of the two ferrite stacks is shown in Figure 1. The tube drive current as represented by i_1; the balancing current by i_x and the cavity feed, by i. With the balancing winding energized the net excitation for each half of the ferrite is $\frac{1}{2}\, i_1$ and the magnetic flux through the two ferrite stacks are equal. The induced voltages v_1 and v_2 are equal but of opposite phase. With the result that $v_2 = -v_1$ and $v = 2v_1$. Thus, the cavity is energized by two equivalent push-pull current sources, each equal to one-half of the value of the physical excitation.

AMPLIFIER CONFIGURATION

To achieve the low output resistance required to satisfy the Robinson Resistance various types of tubes and circuit configurations were investigated for their output resistance. A maximum plate resistance (r_p) of 500Ω is considered acceptable. Based on the tube by itself the beam damping is 4KΩ; with the cavity losses included, the Robinson Resistance is approximately 1.7KΩ, comfortably satisfying the criterion. See Figure 2 for the various circuit configurations considered in the development.

Triodes have low values for plate resistance r_p. In the power range of interest typical values of r_p can be as low as 100 ohms. (e.g. Amperex 8918). Due to the large value of inter-electrode capacitance C_{gp}, typically 75μμF, the tube is usually operated grounded grid, a self-neutralized configuration. The output resistance increases to $r_p+(1+\mu)R_s$. Typically, μ is 40 and R_s must be limited to 10Ω. This configuration is excited from a step down transformer with a high turns ratio, requiring a high value of drive voltage. The power gain is low, usually $\frac{1}{2}\mu$ to $\frac{1}{3}\mu$. Thus, the drive power is approximately 20kW.

Triodes can also be operated as a cathode follower. The output resistance of this configuration is very low $1/g_m$, in the range of 5-10 ohms. The cathode follower is very difficult to stabilize (i.e. maintain a non-oscillatory state) with a resonant load. In addition, the drive voltage must be 11.25kV. Small values of phase shifts between the grid and cathode can cut the tube off.

The triode can be operated grounded cathode with an output resistance of r_p (100Ω) and a drive power of 1KW or less. The stage must be neutralized. Neutralization schemes require equality of phase shifts and matching of component values. They have been developed and work well in narrow band circuits. Due to the broad band application (nearly an octave) and the large value of C_{gp} (75μμF), neutralization is considered very difficult.

Tetrodes can be operated grounded cathode. The value of C_{gp} is in the order of 5μμF or less in the power range of interest. If necessary, broad band neutralization schemes can be employed for stablization. The value of r_p depends on the μ of the tube. High perveance low μ tetrodes in this power range have r_p's in the range of 200 to 1000 ohms.

For example, the EIMAC 4CM300,000 and the Siemens RS2042 have been studied for r_p. Both tubes are rated for 300kW plate dissipation. The results are summarized in the curves of Figure 3. The EIMAC tube has a μ of 110 and the Siemens tube a μ of 170. The plate resistance at comparable quiescent points are almost in the ratio of the μ's. The value of r_p depends on plate current, and to a lesser extent on the value of screen voltage. Both tube appear to satisfy the output resistance requirement. The voltage ratings of the tubes are satisfactory. The EIMAC tube is rated for an E_{bb} of 20kV; the Siemens for 23kV. Two designs have been developed and are summarized in this note.

PLATE RESISTANCE

The plate resistance of a tube has a strong dependency on plate current and is averaged over the operating cycle. The energy extracted from the cavity by the tube is calculated for an rf cycle and is equated to the energy extracted from the cavity by an equivalent resistance.

$$W = \int_0^T \frac{v^2(t)}{r_p(v)} \, dt = \frac{V^2}{2 \; Req} T$$

Where $\nu(t)$ = gap voltage

V = Peak value of gap voltage

T = Period of rf cycle

Req = Average plate resistance

$r_p(v)$ = Plate resistance

From the load line construction, see Figure 4, r_p is known as a function of time. Numerical integration is employed. The independent variable is divided into 12, equal segments over the cycle. The value of Req averaged over the conducting interval of the tube is given by

$$\frac{1}{Req} = \frac{2}{3} \left[\frac{.067}{r(15°)} + \frac{0.5}{r(45°)} + \frac{.933}{r(75°)} \right]$$

AMPLIFIER CIRCUIT

Two circuits have been developed and studied in detail. The performance characteristics have been evaluated for each machine phase and cycle, the worse cases tabulated and compared to the maximum tube ratings.

Figure 5 is the schematic of the one tube Class AB, amplifier employing the EIMAC 300,000 tube. The zero signal plate current is 5A. The grid is excited only during the accelerating phase of the machine and thus the plate dissipation is calculated for a 50% duty cycle. The emission is averaged over an rf cycle. The results of this study is presented in Table III.

In addition the performance of a two tube Class AB, amplifier has been studied and calculated. The two tube driver employs the same tube and zero signal bias as the one tube amplifier. Both series of calculations are presented and compared in Table III.

The load lines for the full voltage cycle and the reduced voltage cycle are presented as Figures 6 and 7. The load locus for the injection phase of the machine is presented in Figure 8. Note that the loci are separated from regions of heavy screen and grid currents.

Due to the large plate current swing of the tube, the plate current and grid voltage surings are not proportional. Corrections were made for the non-linear behavior of the tube by determining a typical current waveform and performing a harmonic analysis on the waveform. A typical large signal current waveform is given in Figure 9. The results of the harmonic analysis are reduced to waveform factors, and are given in Table IV and compared to idealized Class A and Class B waveform factors. Essentially the peak currents are increased 11% over the idealized calculated values.

In summary, the one tube amplifier is operating comfortably within its rating. Except for the plate voltage rating, all parameters are within 50% of the maximum rating.

DRIVE CIRCUIT AND NEUTRALIZATION

The stability of the circuit has been evaluated by employing the Linvill Stability Criterion.[3] Stated in terms of the maximum feedback capacitance (C_{gp}) for which an amplifier is free of sinusoidal and relaxation oscillation.

$$C_{gp} < \frac{2}{\omega g_m \ R_1 R_2} = C_{osc}$$

where ω = the resonant frequency of the load

R_2= Resistive component of load impedance

R_1= Resistive component of source impedance

g_m= Transconductance of tube

The maximum value of C_{gp} for which the circuit is stable is referred to as C_{osc}. R_2 includes the loading due to the cavity, the beam, and the tube plate resistance.

For stability C_{gp} must be less than C_{osc} at each and every point on the load locus for every machine phase and state. Consequently, C_{osc} is evaluated for different loads.

a) unloaded, damping due only to r_p.

$$C_{osc} = \frac{2}{\omega \mu \ R_1}$$

this removes the tube non-linearity from the criterion. With a drive resistance of 50Ω, a μ of 120, and a maximum frequency of 4.2MHz C_{osc} is 13μμF.

b) Cavity loaded, damping due to r_p and the ferrite. The amplifier is linear and with a resonant (cavity) load; the gain A is 40. Thus C_{osc} is evaluated with A instead of μ. C_{osc} is 38μμF. If the cavity is detuned, the impedance is decreased but the real part of the load admittance remains at the value used at resonance and C_{osc} is 38μμF.

c) Beam loaded, with the beam extracting energy from the cavity, the effective load resistance and gain decreases increasing the value of C_{osc} to 53μμF.

The net feedback capacitance is due to C_{gp} (5.6μμF), socket, wiring and stray capacitance. If the total feedback can be kept to 13μμF, the circuit need not be neutralized. The minimum value of C_{osc} is 38μμF. Neutralization might be required to prevent skewing of the pass band of the amplifier, which is best determined experimentally.

In the event the circuit requires neutralization the push-pull drive transformer can be employed for wideband neutralization. The scheme is a modification of the commonly employed narrow band Rice neutralization scheme. A simplified circuit representing the feedback and neutralization elements is given in Figure 10. Basically, the elements C_N, L_1, C_{gp}, and L_2 form a bridge. When balanced, the feedback from anode V_A to V_{GN} is nulled. V_G is ½ V_{GN} due to the input transformer. The balance and input transformer are frequency insensitive.

The input specifications are given in Figure 11. The input circuit is a broad band tuned circuit with a Q of 1.5. If the driver stage is matched to the transformer the Q is 0.75 and the response is flat to within ± 6%.

Second Design

A second design employing the Siemens RS2042SK Tetrode is given in Figure 12. This tube has a larger value of μ than the EIMAC 4CM300,000G. This is reflected in the larger values for the beam damping resistance and the smaller values for C_{osc} and C_{gp}. Neutralization for both circuits are comparable. The beam damping is satisfactory. Otherwise the electrical performance of both circuits are quite similar. The performance results of this circuit is summarized in Table V.

Balanced Cavity Excitation

The figure-of-eight coupling loop and the cavity drive winding do not maintain geometric symmetry within the cavity. See Figures 5 and 12. To the extent that the coefficient of magnetic cooling between the drive winding and the coupling loop is not unity, the voltages ν_1 and ν_2 are not equal. (see Fig. 1). This unbalance can allow the common mode to be excited within the cavity. If upon investigation it is found that this mode is indeed excited and must be suppressed, the cavity excitation can be modified as to maintain geometric symmetry. This scheme is illustrated in Figure 13.

References:

1. M. Meth, A. Ratti, Push-Pull Operation of the Cavity, Booster Tech. Note 84, July, 1987.

2. M. Plotkin, Booster Proton Cavity with Voltage Reduction During the Cycle, Booster Tech. Note 85, July 1987.

TABLE I

POWER REQUIREMENTS
PER STATION

MACHINE STATE	CAVITY LOSS KW	BEAN POWER KW	AMPLIFIER POWER KW	ROBINSON RESISTANCE
Injection (90KV)	47.7	0	47.7	
Minimum Acceler. (90KV)	47.7	37.9	85.6	
Maximum Acceler.				
90KV (Ψ_S=17°)	93.7	66.3	160.	3.8KΩ
70KV (Ψ_S=22.1°)	49.5	66.3	115.8	2.3KΩ
Ejection				
90 KV (Ψ_S=0°)	93.7	0	93.7	
70 KV (Ψ_S=0°)	49.5	0	49.5	

$.75 \times 10^{13}$ PROTONS/BUNCH

TABLE II

CAVITY DRIVE CURRENT PER STATION

CURRENT: PEAK VALUE OF FUNDAMENTAL (AMPS).

MACHINE STATE	CAVITY CURRENT	BEAM CURRENT IN PHASE	BEAM CURRENT QUADRATURE PHASE	TOTAL CURRENT
Injection				
90 KV	4.24	0	9.05	10.86
Minimum Acceler.				
90 KV	4.24	3.37	8.41	11.34
Maximum Acceler.				
90 KV	8.33	5.90	0	14.3
70 KV	5.65	7.58	0	13.23
Ejection				
90 KV	8.33	0	0	8.33
70 KV	5.65	0	0	5.65

TABLE III

SUMMARY OF TUBE PERFORMANCE

TUBE PERFORMANCE	TWO TUBE DRIVER: REDUCED VOLTAGE CYCLE	TWO TUBE DRIVER: FULL VOLTAGE CYCLE	ONE TUBE DRIVER: REDUCED VOLTAGE CYCLE	ONE TUBE DRIVER: FULL VOLTAGE CYCLE	TUBE ABSOLUTE MAXIMUM RATING
E_{BB}	13 KV	13 KV	13 KV	13 KV	20 KV
E_{c2}	1 KV	1 KV	1.1 KV	1.1 KV	2 KV
E_{c1}	-270 V	-270 V	-300 V	-300 V	
Plate Dissipation					
Short Term					
Injection	112 KW	112 KW	205 KW	205 KW	
Max.Acceler.	109 KW	91 KW	193 KW	155 KW	
Average 50% Duty Cycle	58 KW	83 KW	135 KW	125 KW	300 KW
Screen Dissipation	180 Watts	300 Watts	385 Watts	660 Watts	6 KW
Plate Current					
Peak	32.5 A	34 A	63 A	65 A	
Short Term Average	12.8 A	13.1 A	23.75A	24.25A	50 A
Screen Current					
Peak	1 A	2 A	2 A	4 A	
Average	0.2 A	0.3 A	.35A	0.6 A	
Grid Current	0	0	0	0	
Average Plate Resistance	340 Ω	260 Ω	210 Ω	186 Ω	
Beam Damping Incl. Cavity Per Station	1.08KΩ	750 Ω	1.1KΩ	965 Ω	
Maximum Grid Excitation Peak Volts	210	210	280	280	
Power	441 Watts	441 Watts	784 Watts	784 Watts	
Maximum Anode Input Power	334 KW	342 KW	309 KW	315 KW	

EIMAC 4CM 300,000G
Class AB_1
Zero Signal Plate Current = 5A

TABLE IV

WAVEFORM ANALYSIS

	$\frac{I_1}{I_{AV}}$	$\frac{I_{PEAK}}{I_1}$	$\frac{I_P}{I_{AV}}$	THEO-RETICAL EFFICIENCY
Class A	1.0	2.0	2.0	50%
CLASS B	1.57	2	3.14	78.5%
CLASS AB (Measured) ZERO SIGNAL CURRENT = 5A	1.42	2.22	3.17	71%

Figure 7
LOCUS
MAXIMUM ACCELERATION
70KV CYCLE
ONE TUBE DRIVER

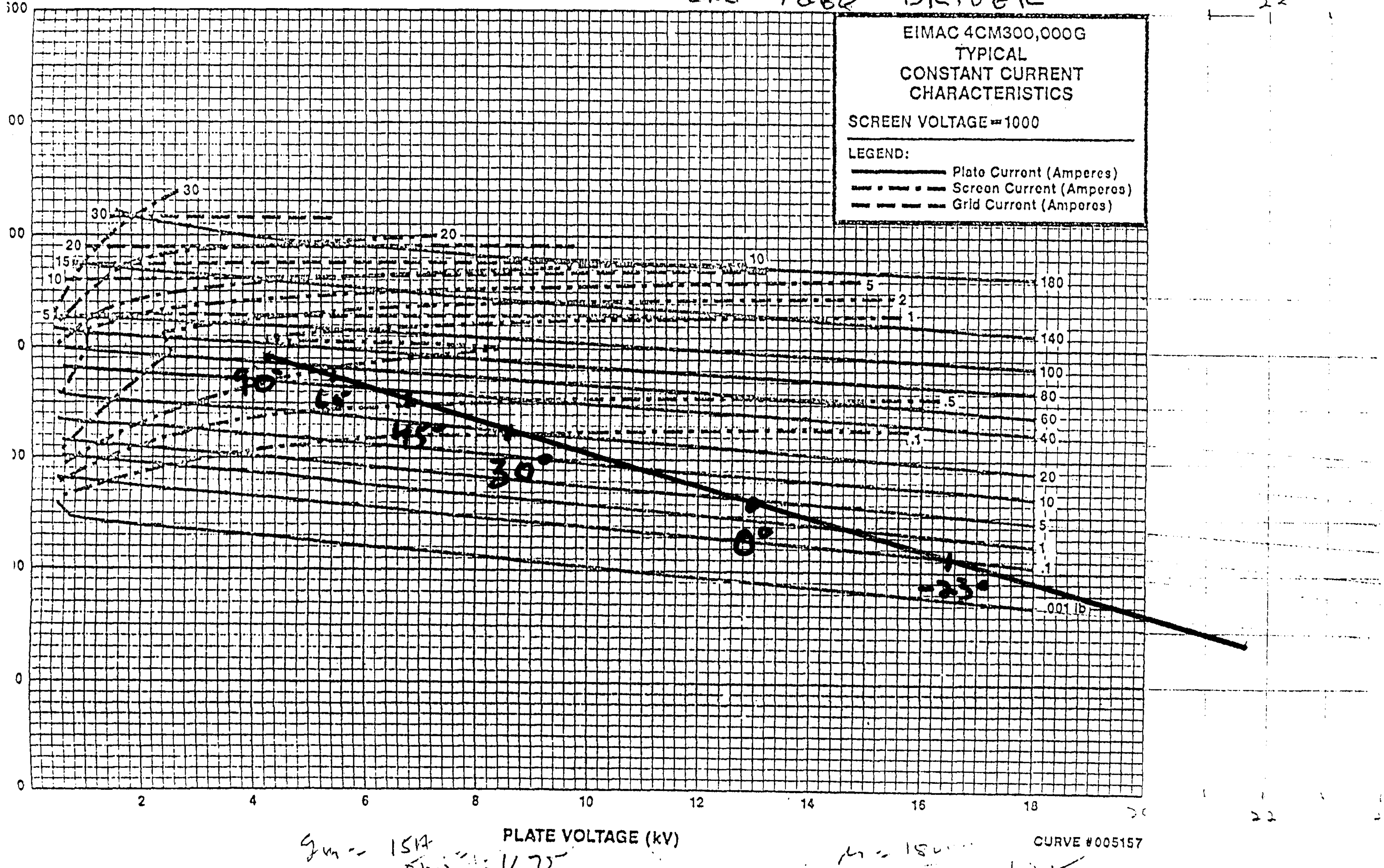


Figure 6
LOCUS
MAXIMUM ACCELERATION
90KV CYCLE
ONE TUBE DRIVER

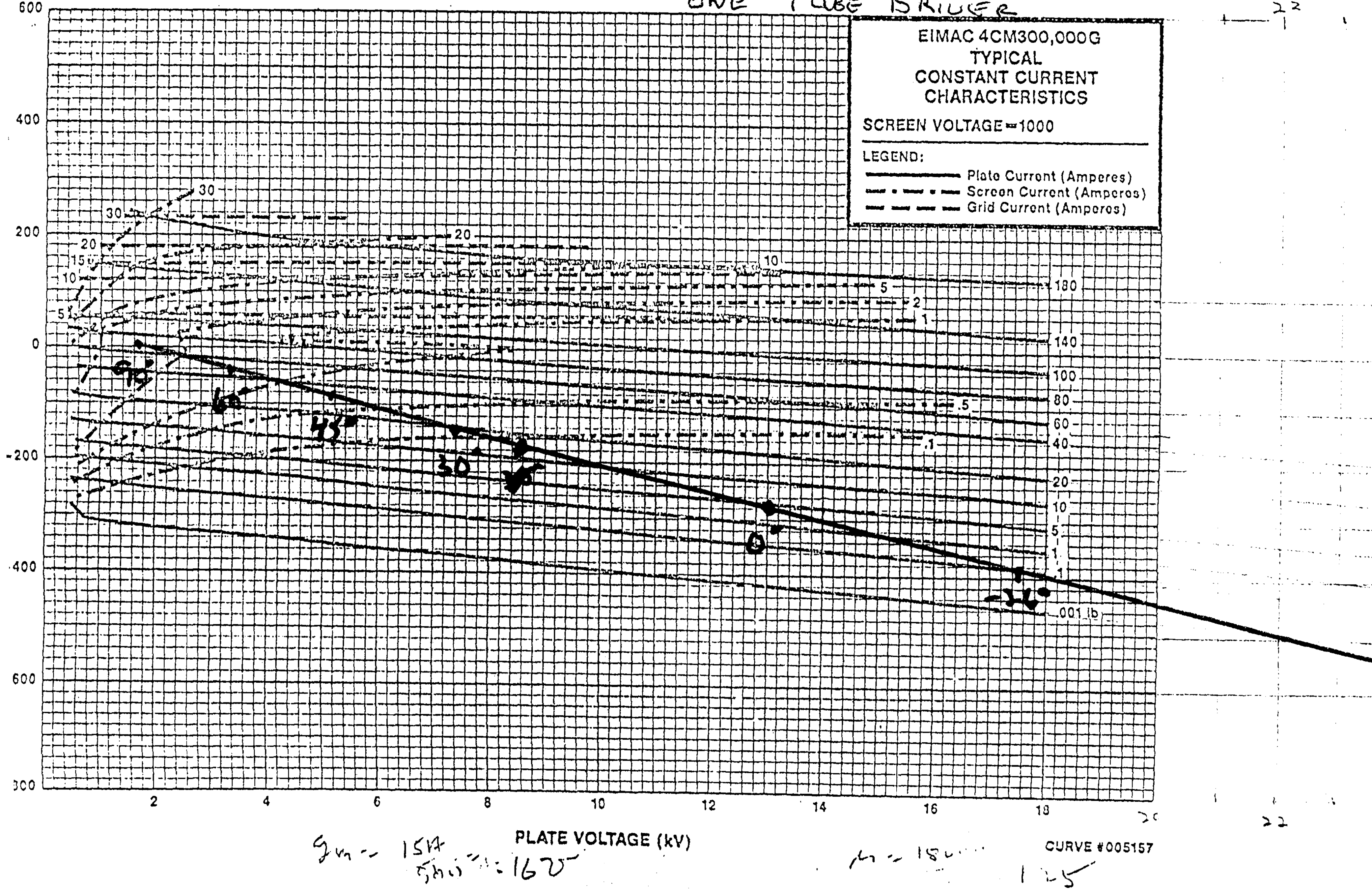
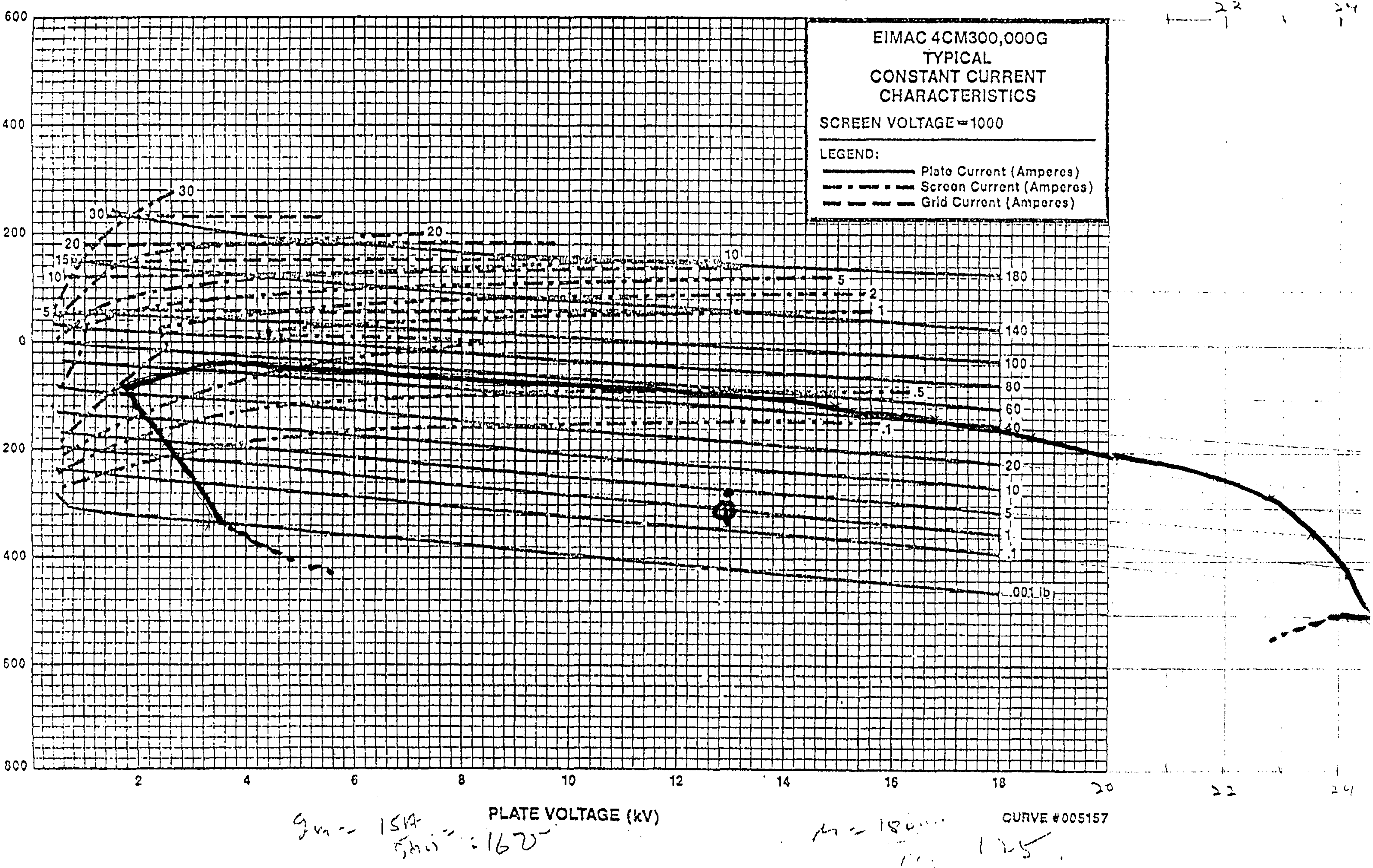


Figure 8
LOCUS
ONE TUBE DRIVER
$\psi_s = 0°$



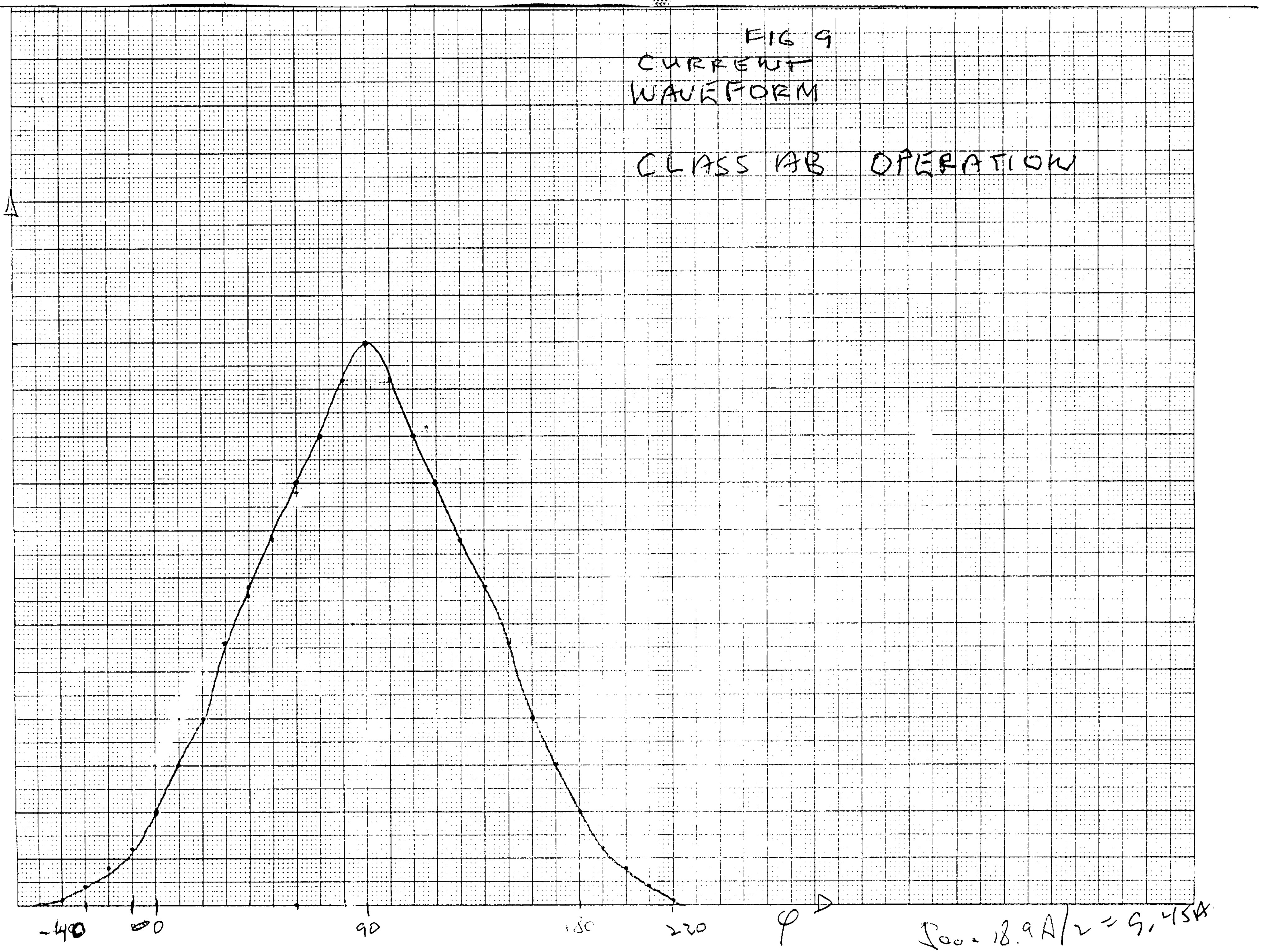
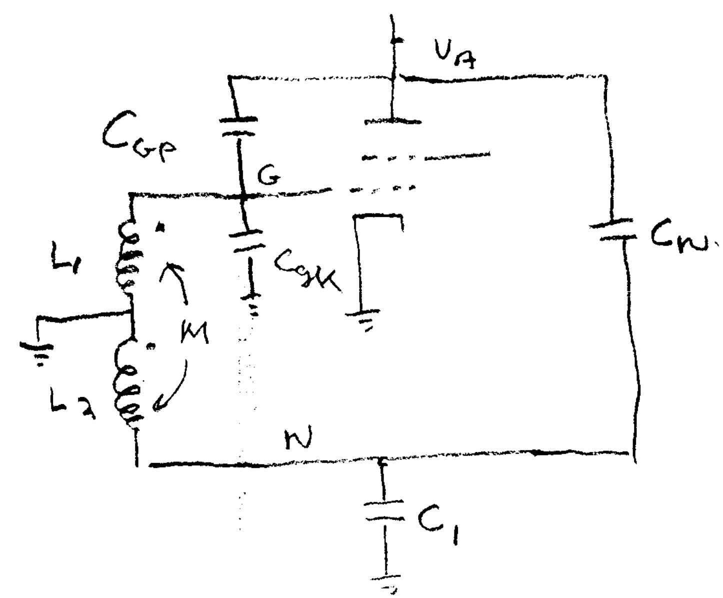


FIG 9
CURRENT
WAVEFORM
CLASS AB OPERATION
-40
0
90
180
220
φ
I_{00} = 18.9 A/2 = 9.45A

FIG 10

WIDEBAND NEUTRALIZATION



$$C_N L_1 = C_{GP} L_2$$
$$V_G = \frac{1}{2} V_{GN}$$

INDEPENDENT OF FREQUENCY

$$C_1 = C_{gK}$$

Figure 11

INPUT CIRCUIT AND NEUTRALIZATION

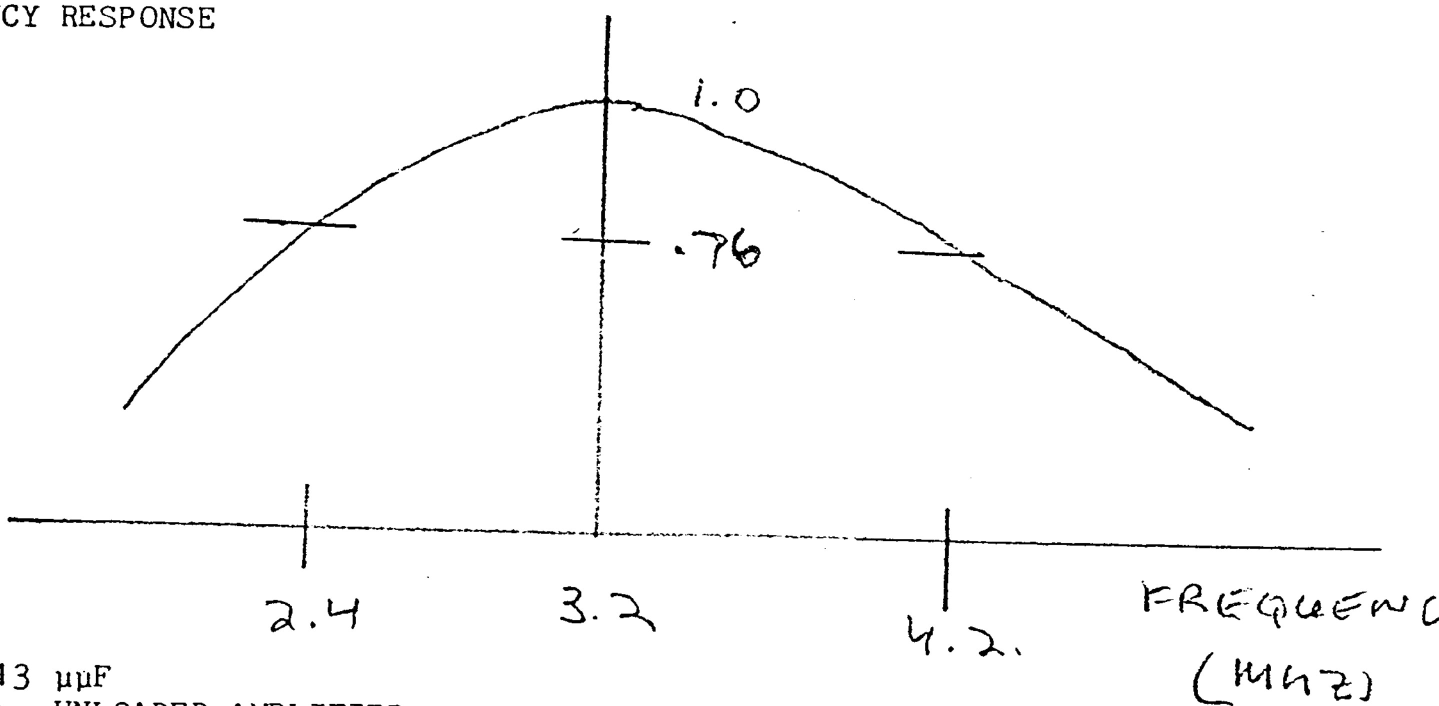
R_{in} = 50 Ω

C_{in} = 1500 μμF

BROAD BAND (TUNED) INPUT Q = 1.5

P_{in} = 784 WATTS

FREQUENCY RESPONSE



C_{osc} = 13 μμF
UNLOADED AMPLIFIER

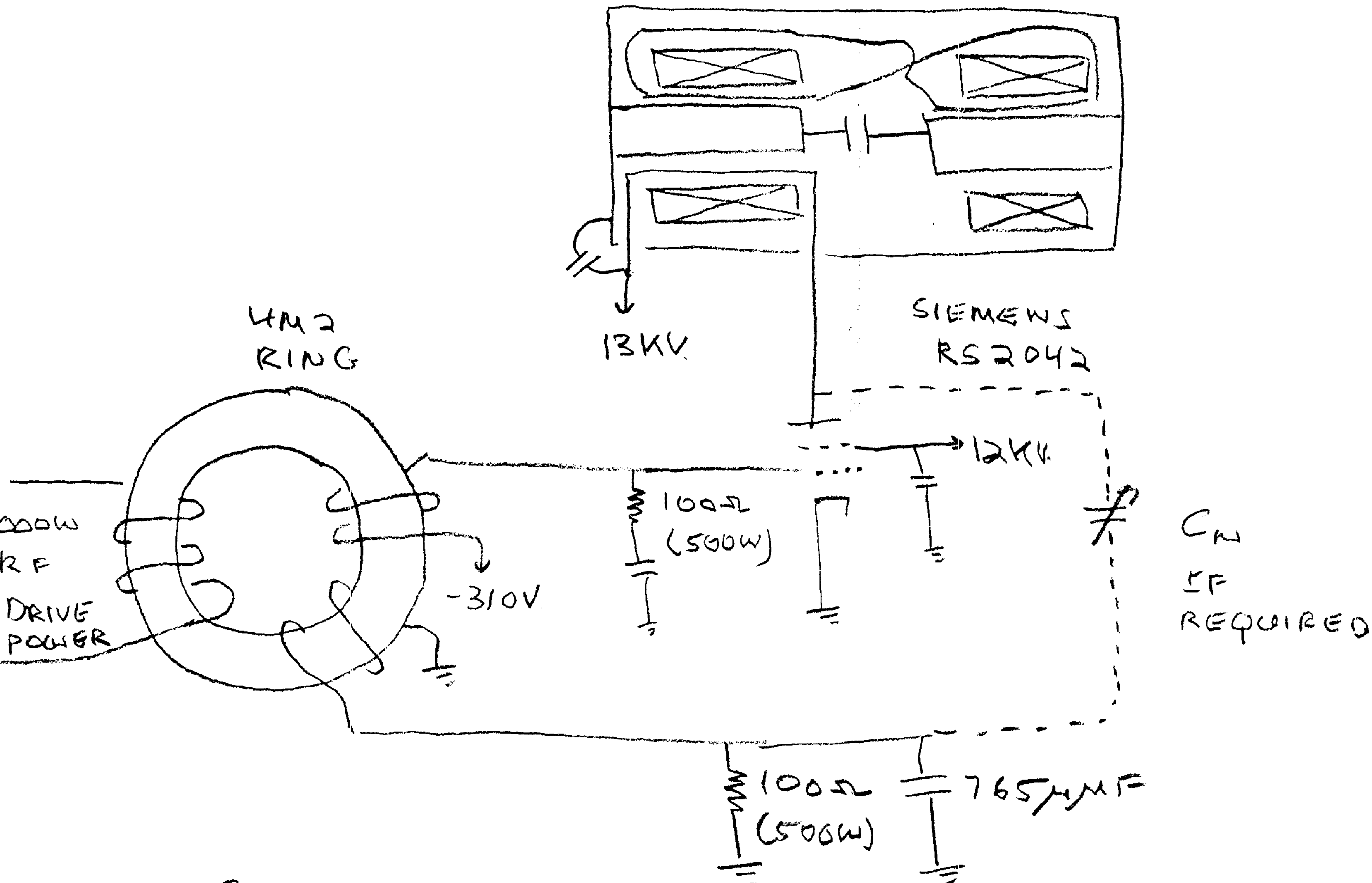
= 38 μμF
CAVITY LOADED AMPLIFIER

= 53 μμF
CAVITY AND BEAM LOADED AMPLIFER

C_F = 5.6 μμF + Wiring = 13 μμF

WILL EXPERIMENTALLY DETERMINE NECESSITY FOR

EBAND NEUTRALIZATION.



C_{osc} = 41μμF
C_{gp} = 4.5μμF
C_F = 12μμF

FIG 12
SCHEMATIC OF RF
POWER AMPLIFIER

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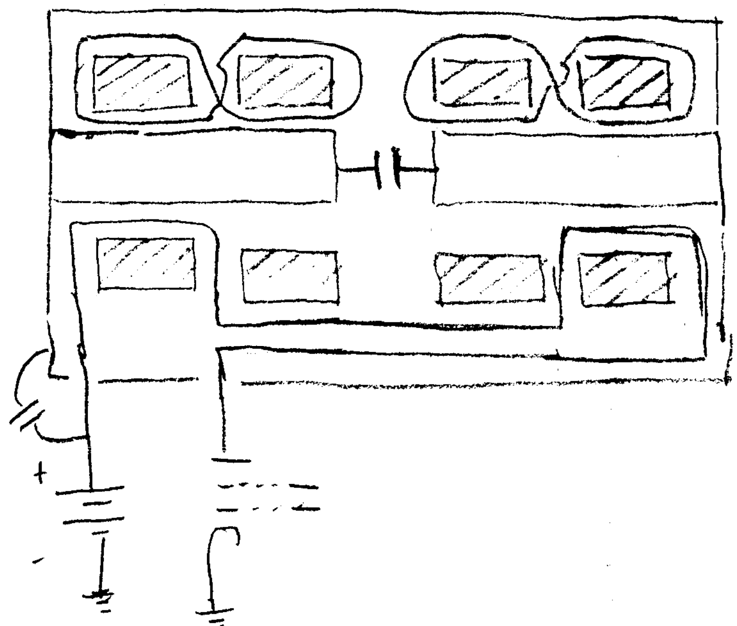


FIGURE 13

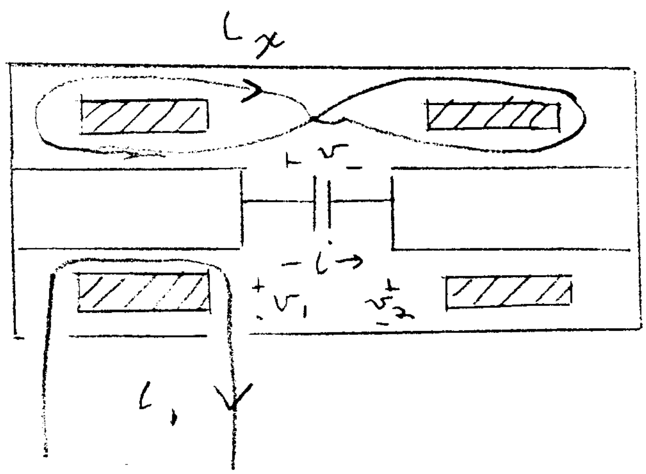
SYMMETRICAL EXCITATION OF CAVITY USING A ONE TUBE DRIVER.

TABLE V

SUMMARY OF TUBE PERFORMANCE

TUBE PERFORMANCE	REDUCED VOLTAGE CYCLE	FULL VOLTAGE CYCLE	TUBE ABSOLUTE MAXIMUM RATINGS
E_{BB}	13 KV	13 KV	23 KV
E_{C2}	1.2KV	1.2KV	2.2KV
E_{C1}	-310 V	-310 V	-1200 V
PLATE DISSIPATION			
SHORT TERM			
INJECTION	210 KW	210 KW	
MAXIMUM ACCELERATION	190 KW	163 KW	
AVERAGE 50% DUTY CYCLE	132 KW	126 KW	300 KW
SCREEN DISSIPATION	480WATTS	720WATTS	5 KW
PLATE CURRENT			
PEAK	62 A	64 A	300 A
SHORT TERM AVERAGE	23.5A	24.1A	50 A
SCREEN CURRENT			
PEAK	2 A	4 A	
AVERAGE	0.4A	0.6A	
GRID CURRENT	0	0	
AVERAGE PLATE RESISTANCE	516 Ω	500 Ω	
BEAM DAMPING INCLUDING CAVITY PER STATION	1.76KΩ	1.60KΩ	
MAXIMUM GRID EXCITATION			
PEAK VOLTS	310	310	
POWER	960 Watts	960 Watts	
MAXIMUM ANODE INPUT POWER	306 KW	313 KW	

Siemens
RS2042SK
Class AB
Zero Signal Plate



NET MMF THROUGH LOOP = $i_1 - 2i_x = 0$

$$i_x = \frac{1}{2} i_1$$

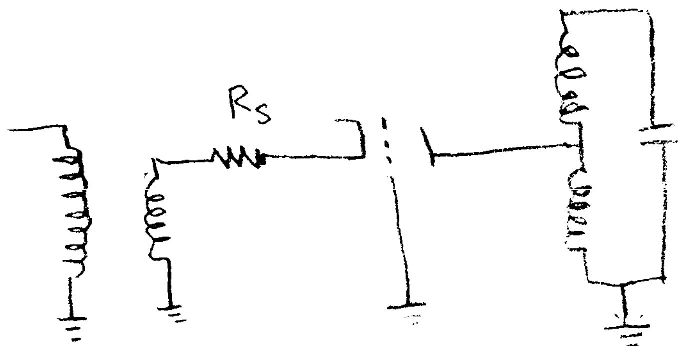
$$i = i_1 - i_x = i_x = \frac{1}{2} i_1$$

$$v_2 = -v_1$$

$$v = 2v_1$$

Figure 1

CROSS COUPLING LOOP AND CAVITY DRIVE

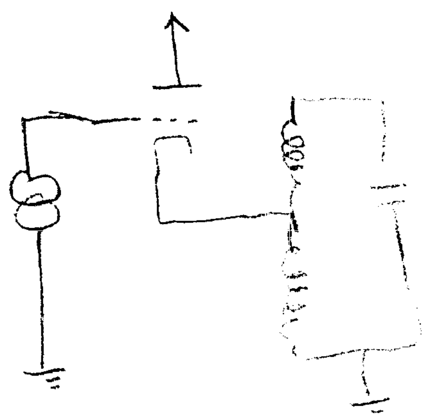


GROUNDED GRID

SELF NEUTRALIZED

$R_{OUT} = r_p + (1+\mu)R_S$

INPUT POWER AND INPUT XFMR ARE PROBLEMS



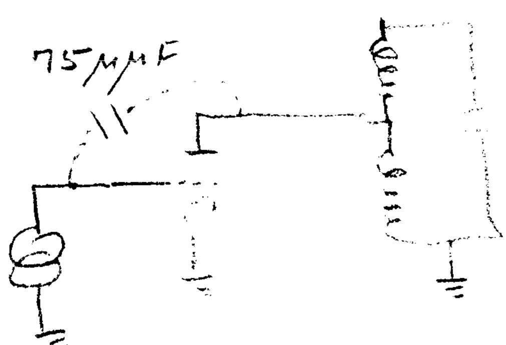
CATHODE FOLLOWER

VERY LOW R_{OUT}

CUT-OFF PROBLEM

STABILITY PROBLEM

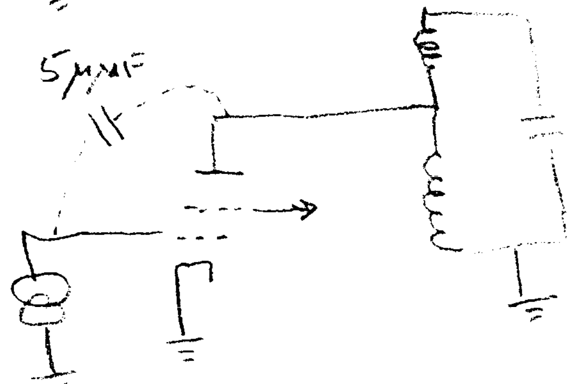
INPUT VOLTAGE PROBLEM



GROUNDED CATHODE TRIODE

LOW r_p

DIFFICULT NEUTRALIZATION



TETRODE

HIGH PERVEANCE

LOW μ

MODERATE r_p

C_{GP} MANAGEABLE

FIGURE 2

CIRCUIT CONFIGURATION

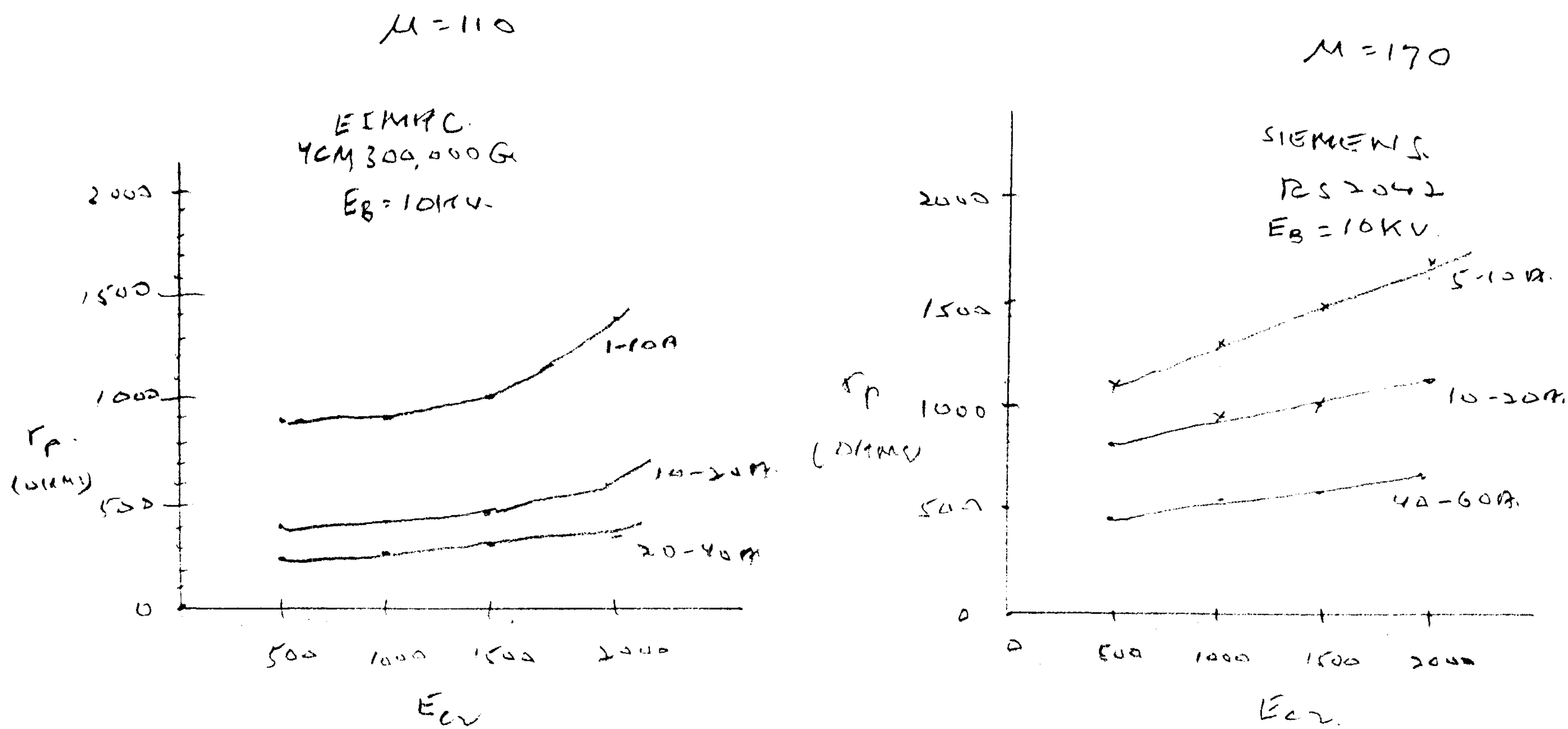
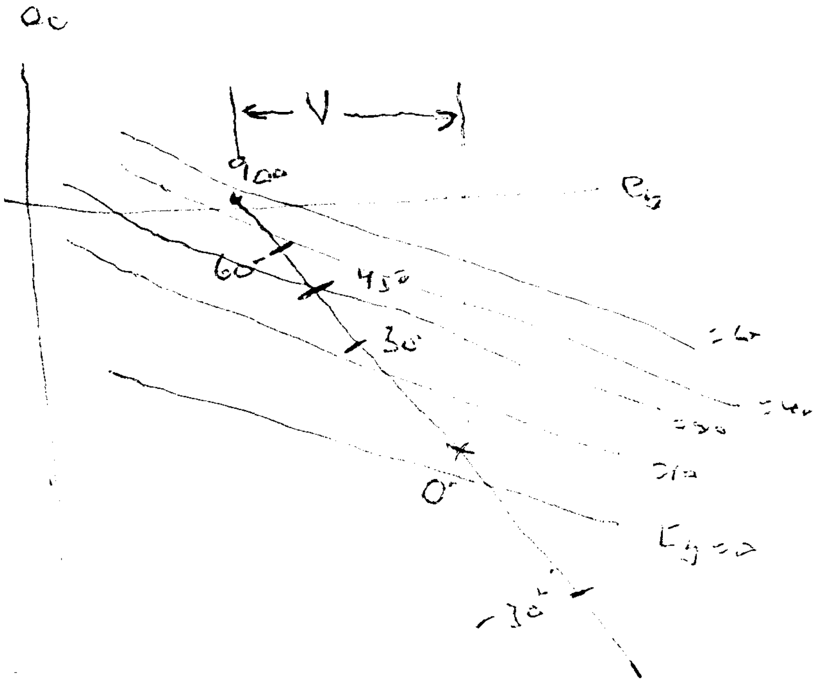


Figure 3

PLATE RESISTANCE OF TWO TETRODES AS A FUNCTION OF OPERATING POINT



$$W = \int_0^T \frac{v^2(t)}{r_p(t)}\,dt = \frac{V^2}{2R_{eq}}T$$

Two Tube Class B

$$\frac{1}{R_{eq}} = \frac{2}{3}\left[\frac{.067}{r(15°)} + \frac{.5}{r(45°)} + \frac{.933}{r(75°)}\right]$$

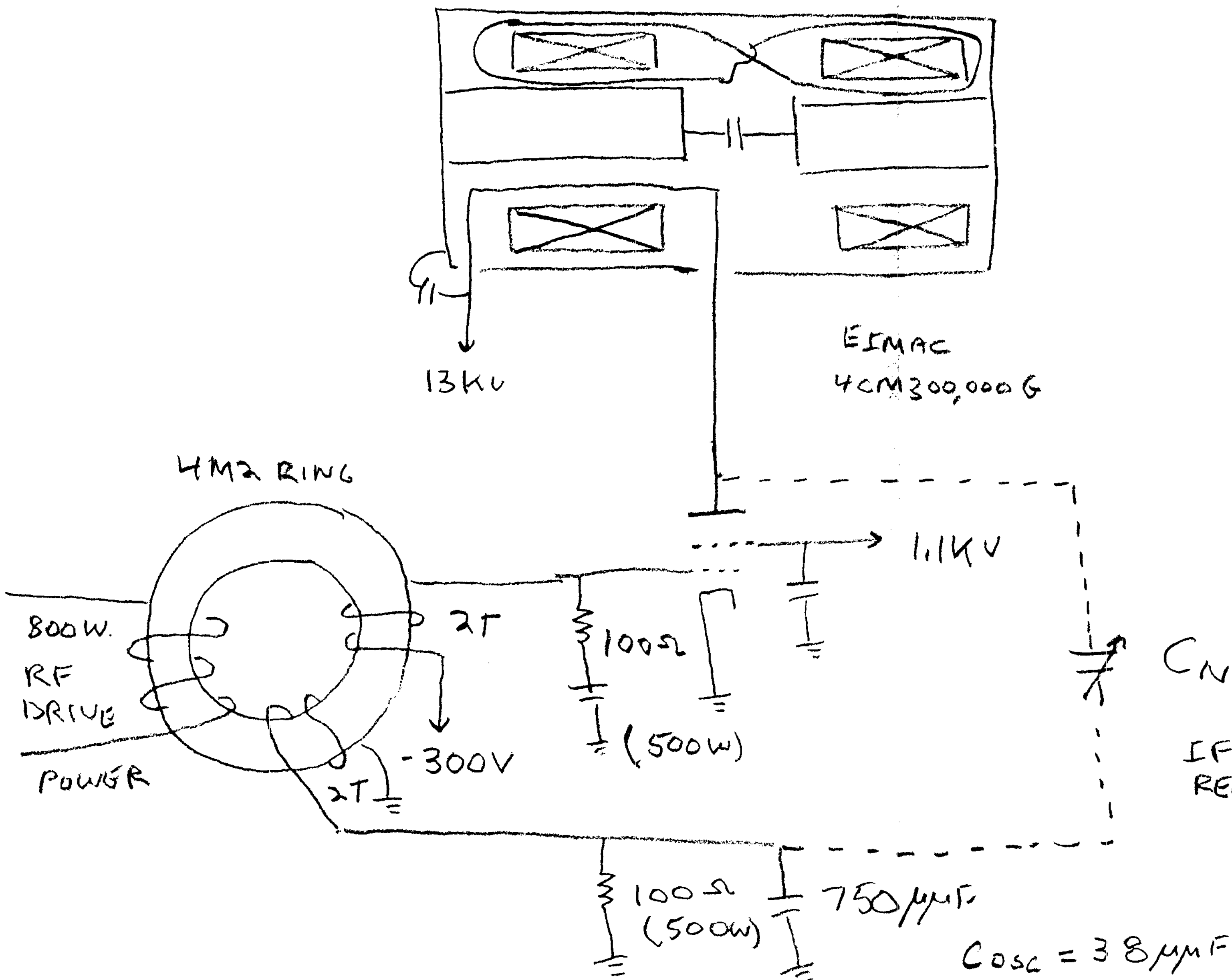
One Tube Class B

$$\frac{1}{R_{eq}} = \frac{1}{3}\left[\frac{.067}{r(15°)} + \frac{.5}{r(45°)} + \frac{.933}{r(75°)}\right]$$

FIGURE 4
AVERAGING OF PLATE RESISTANCE

FIG 5

SCHEMATIC OF RF POWER AMPLIFIER



$C_{osc} = 38 \mu\mu F$
$C_{GP} = 5.6 \mu\mu F$
$C_F = 13 \mu\mu F$

[illegible signature]
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