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TECHNICAL REPORT ECOM-02253-2

A STUDY OF HIGH-POWER ELECTROSTATICALLY
FOCUSED KLYSTRONS

PROGRESS REPORT NO. 2

by

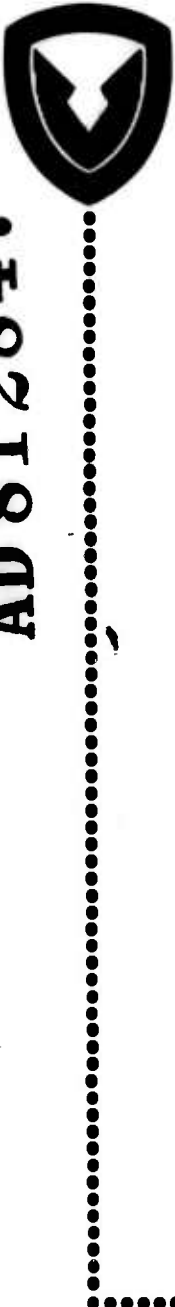
T. Hugo Luchsinger and Walter R. Day

April 1967

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ECOM

UNITED STATES ARMY ELECTRONICS COMMAND • FORT MONMOUTH, N.J.

Contract No. DA 28-043 AMC-02253(E)



LITTON INDUSTRIES
ELECTRON TUBE DIVISION

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FOCUSED KLYSTRONS

REPORT NO. 2

1 August 1966 to 31 October 1966

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Sponsored by

Advanced Research Projects Agency, ARPA Order No. 436

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PURPOSE

The purpose of this program is to study the feasibility of a high-power, broadband C-band electrostatically focused klystron suitable for use in phased array systems.

Specifically, this program will investigate the feasibility of employing higher perveance beams in ESFK's. A higher beam perveance results in better gain times bandwidth and efficiency times bandwidth characteristics and in lower beam voltages for a given beam power level.

Even though the ultimate application for the device is in C-band, the experimental work of this program will be conducted in S-band to utilize existing designs and test equipment. However, consideration will be given to evaluate all the experimental results with regard to C-band tubes.

The electrical design objectives are the following:

Frequency	S-band
Peak rf power output (nom)	250 kw
Cathode voltage	40 kV (max)
Modulating anode voltage	Variable between 30 and 56 kV
Beam perveance	Variable between 1.0×10^{-6} to $2.5 \times 10^{-6} \text{ A/V}^{3/2}$
Gun perveance	$1.5 \times 10^{-6} \text{ Amp/V}^{3/2}$.

The work prepared under this contract was made possible by the support of the Advanced Research Projects Agency under Order No. 436, under the technical guidance of the United States Army Electronics Command.

ABSTRACT

The L-5114 experimental electrostatically focused klystron with variable beam perveance has been assembled and successfully exhausted without any major problems.

Further work with the resistance network analogue has been done to check the lens system on the extreme high side ($k=2.5 \times 10^{-6} A/V^{3/2}$) of the variable beam perveance.

Hot test of the tube has been started and the initial results obtained look promising.

Studies on a triple gap extended interaction cavity have been made. This cavity is scaled to C-band and the assumed perveance is $2.0 \times 10^{-6} A/V^{3/2}$.

Also some studies on beam power and perveance limits for electrostatically focused klystrons as functions of operating frequency have been made.

1.0 FACTUAL DATA

1.1 INTRODUCTION

The primary goal of this program is to investigate the feasibility of employing higher perveance beams in electrostatically focused klystrons (ESFK). Until now only beam perveances of up to $1.0 \times 10^{-6} \text{ A/V}^{3/2}$ have been successfully employed in ESFK's.

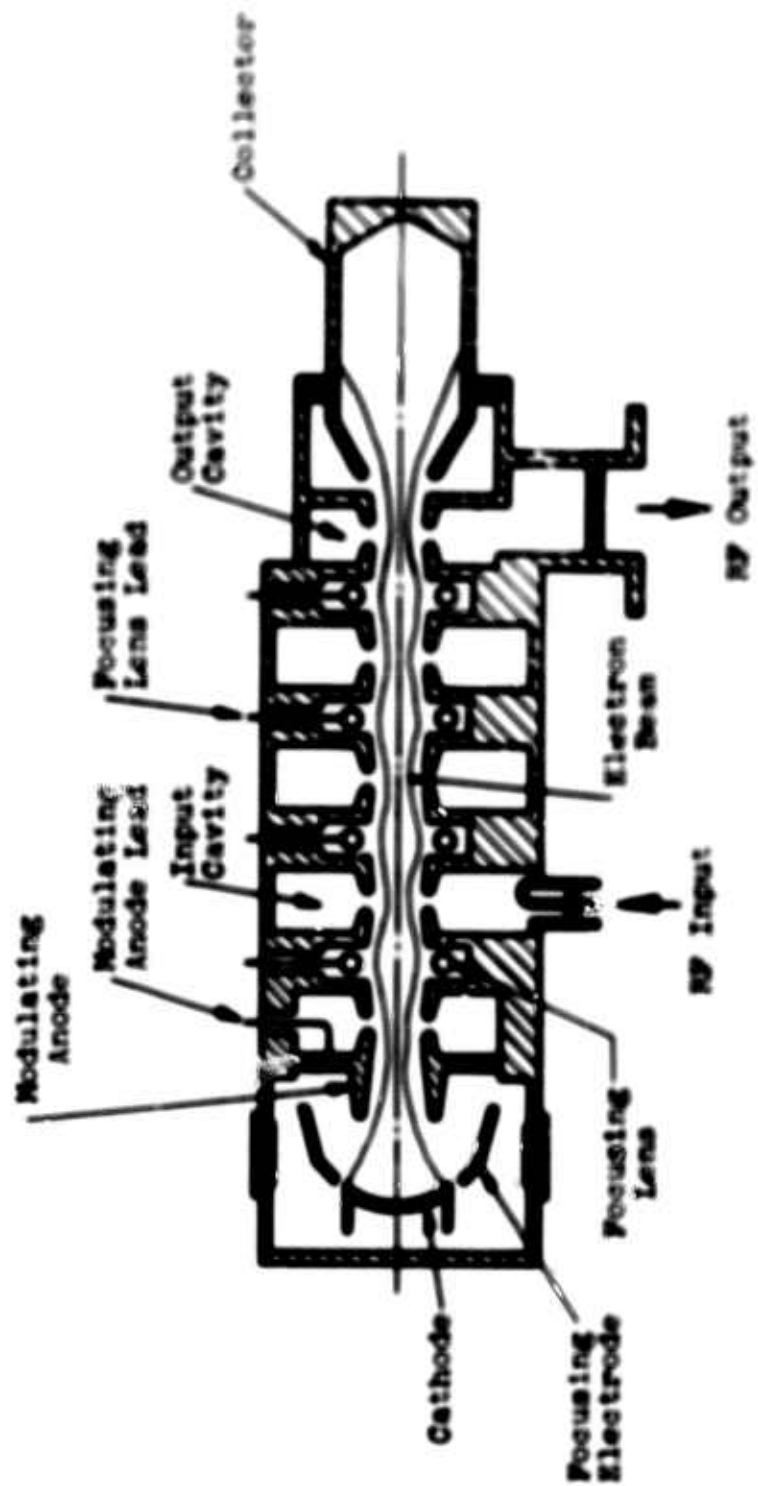
The klystron under development has the following design objectives:

Frequency	3000 MHz (nominal)
Peak rf power output	Variable between approx 130 and 320 kW
Cathode voltage	40 kV
Gun perveance	$1.5 \times 10^{-6} \text{ A/V}^{3/2}$
Beam perveance	Variable between 1.0×10^{-6} and $2.5 \times 10^{-6} \text{ A/V}^{3/2}$
Modulating anode voltage	Variable between 30 and 56 kV
Beam current	Variable between 8 and 20 amps
RF pulse length	10 μsec
Duty	.001
Gain	36 db

1.2 TUBE CONSTRUCTION AND PROCESSING

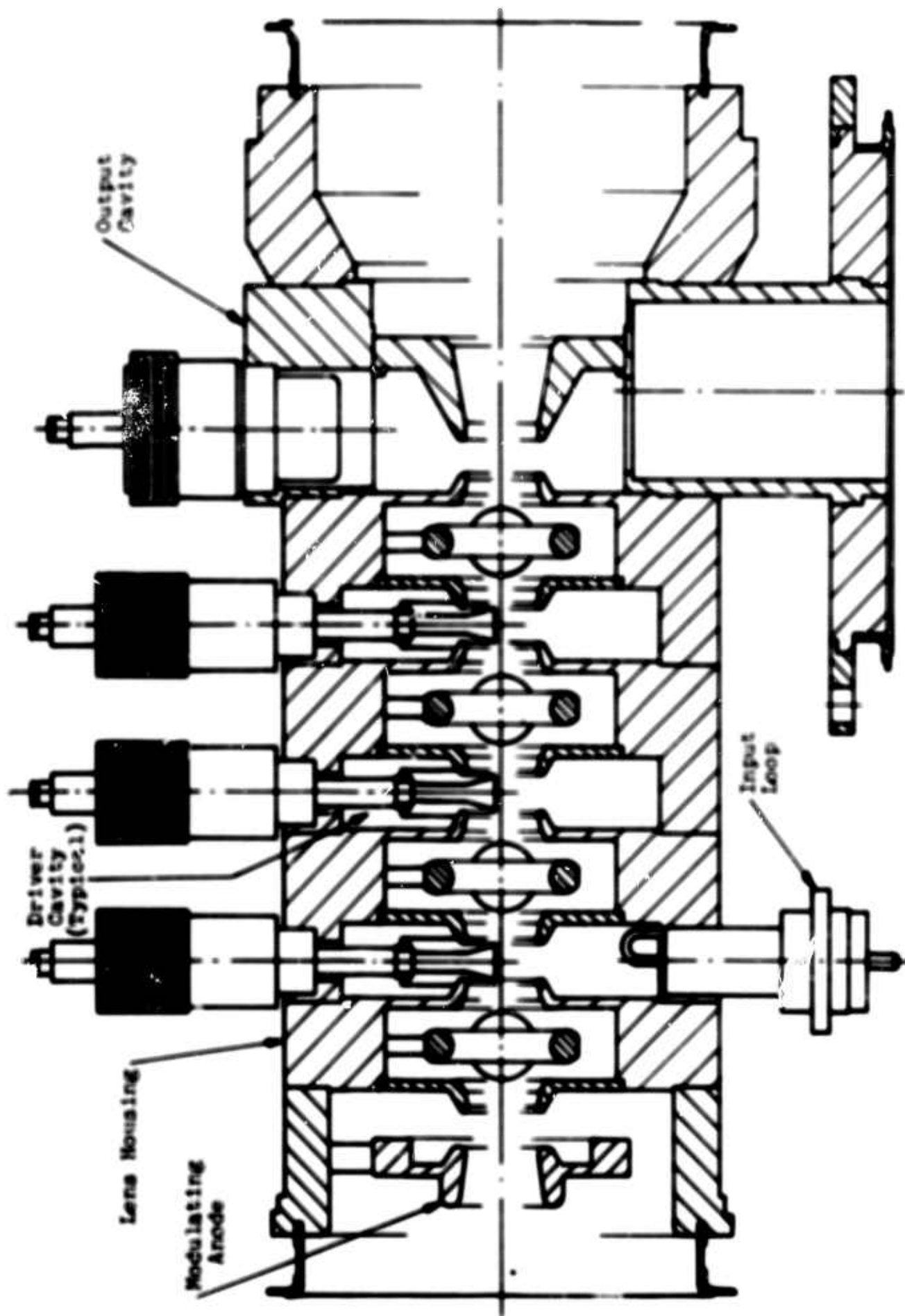
A schematic view of the tube is shown in Fig. 1. The tube is made up from the following major subassemblies:

- A. Main body (Figure 2)
- B. Gun with gun ceramic (Figure 3)



SCHEMATIC LAYOUT OF THE TUBE

Fig. 1



MAIN BODY ASSEMBLY L-5114
 FIG. 2



GUN WITH GUN CERAMIC
L-5115

Fig. 3

- C. Collector with collector ceramic (Figure 4)
- D. RF output window (Figure 5)
- E. Exhaust tubulation with 11/sec Vac-Ion pump.

B, C, D and E are attached to the tube by means of weld flanges.

The main body, which is assembled in one final braze, consists of the following subassemblies (starting from the gun weld flange):

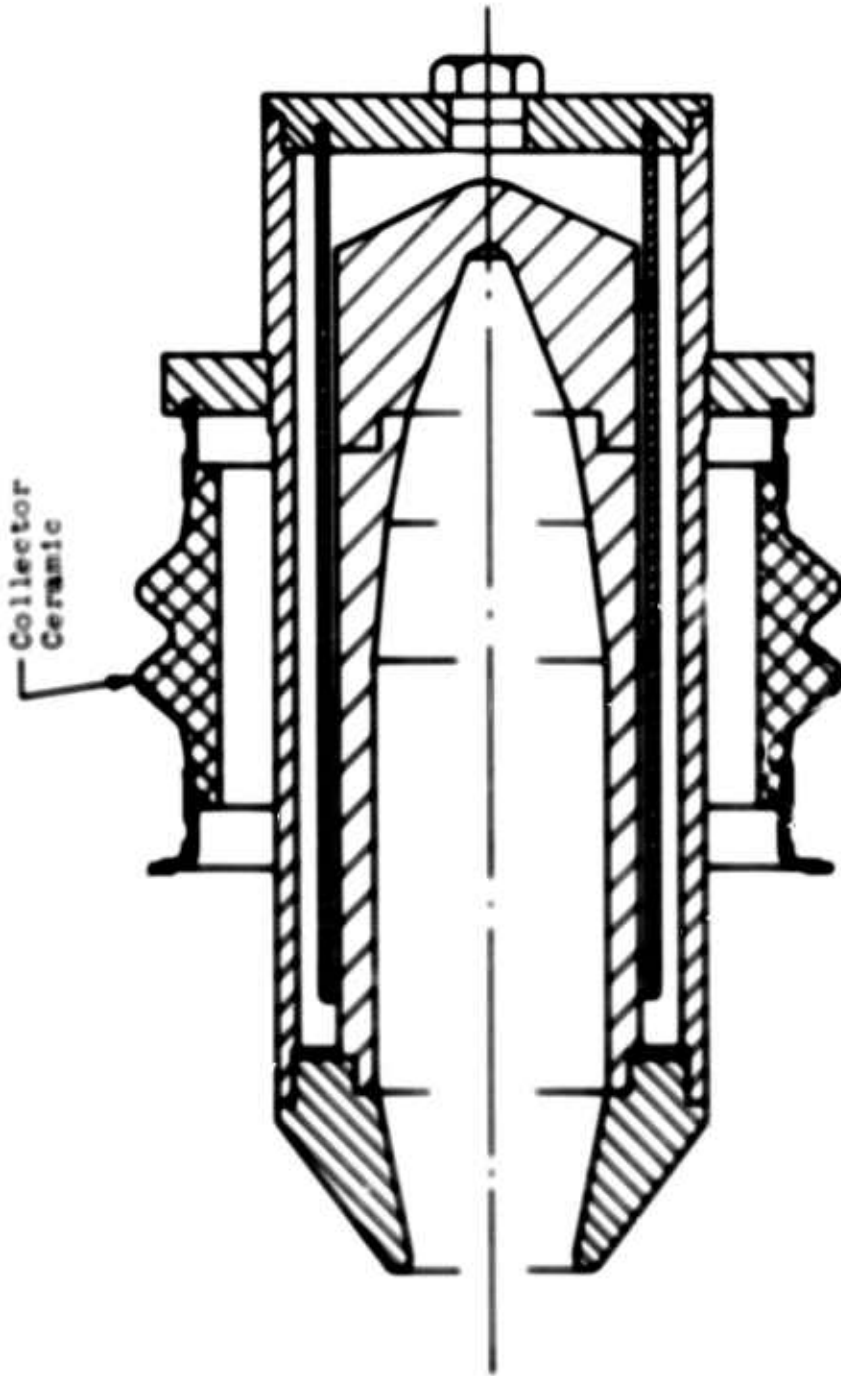
- a. Modulating anode
- b. Lens housing
- c. Three driver cavities
- d. Output cavity.

Each of these subassemblies is brazed in several steps by using brazing alloys of different brazing temperatures.

The modulating anode subassembly consists of the modulating anode with three support ceramics, the high voltage feedthrough and the weld flange for the gun ceramic.

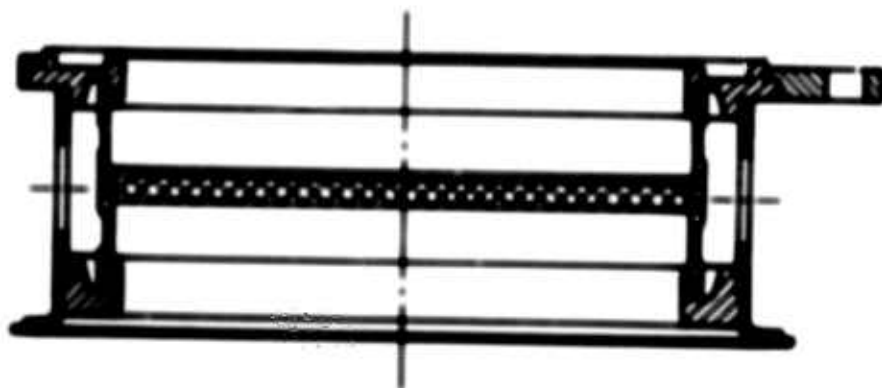
The first lens housing is a subassembly by itself. It consists of a lens system with the high voltage feedthrough. The measured resonance frequency of the complete lens housing is 3726 MHz. This frequency is the same for all following lens housings and is far outside of the operating band of the tube.

Following the first lens housing are three driver cavity subassemblies. Each of them consists of a lens system with the high voltage feedthrough and a capacitive tuner. In addition, the first driver cavity (input cavity) is equipped with the rf input loop. To reduce instabilities, the first two driver cavities are partly iron plated. The measured Q_0 is 1600 compared with the Q_0 of the all copper penultimate cavity of 3200.



COLLECTOR WITH COLLECTOR CERAMIC
L-511A

FIG. 4



PP OUTPUT WINDOW
L-5114

Fig. 5

The output cavity consists of an inductive tuner, the waveguide and the weld flange for the rf output window and the weld flange for the collector ceramic. Also a weld flange for the exhaust tubulation is located in this sub-assembly. The unloaded Q_0 of the output cavity is 4000, the loaded Q_L is 45. The circuit efficiency is

$$\eta_c = 1 - \frac{Q_L}{Q_0} = 1 - \frac{45}{4000} = .989$$

$$\eta_c = 98.9\%$$

Before the gun assembly was welded to the tube, the cathode assembly was preglowed in a bell jar. The preglowing of a gun actually used in a tube has two important meanings.

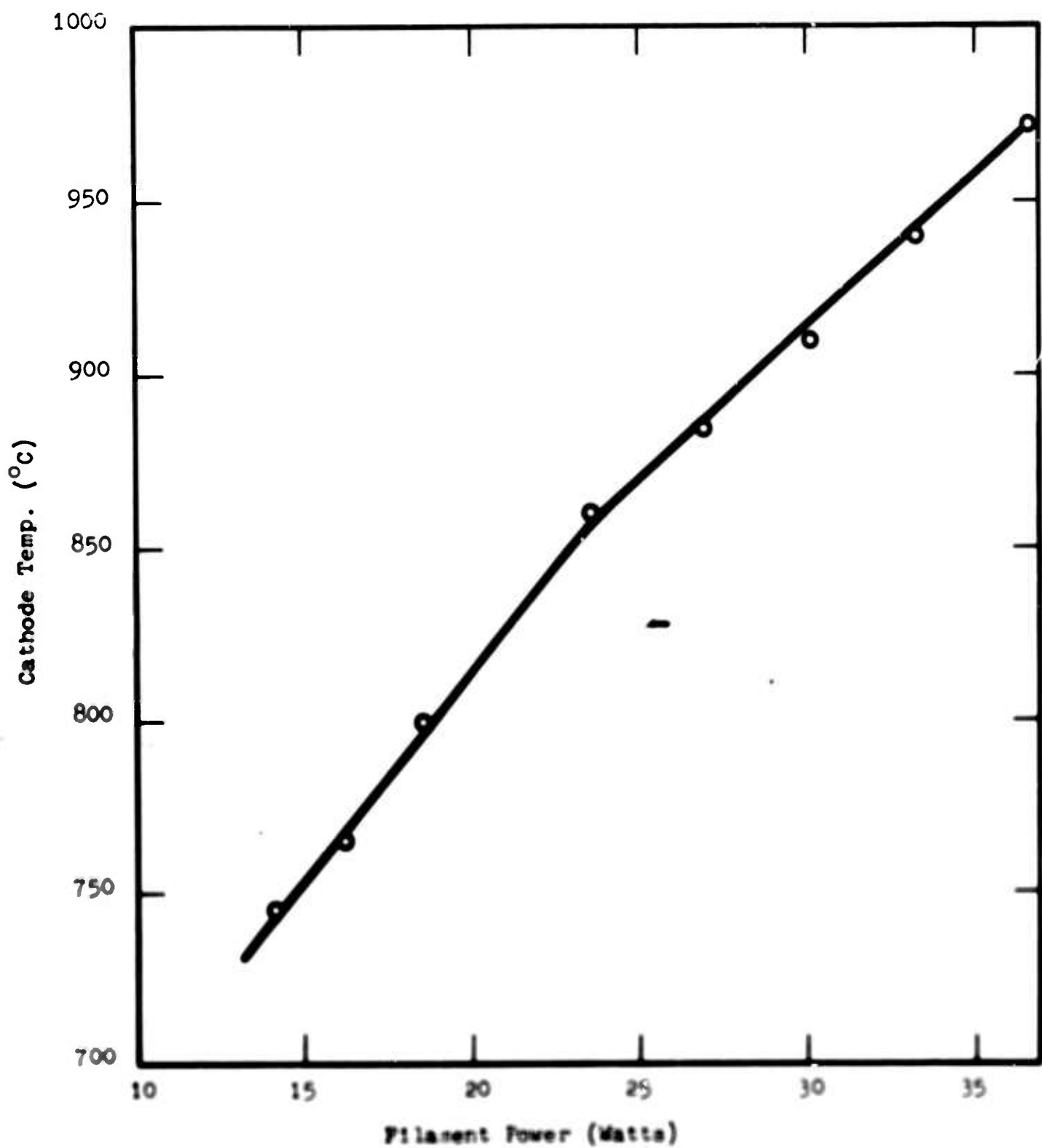
- A. Determination of required filament power,
- B. Final check of the gun for any shorts and open leads under full operating conditions.

Figure 6 shows cathode temperature vs filament power.

After the tube was completed and leak checked, it was exhausted according to the standard Litton exhaust procedure.

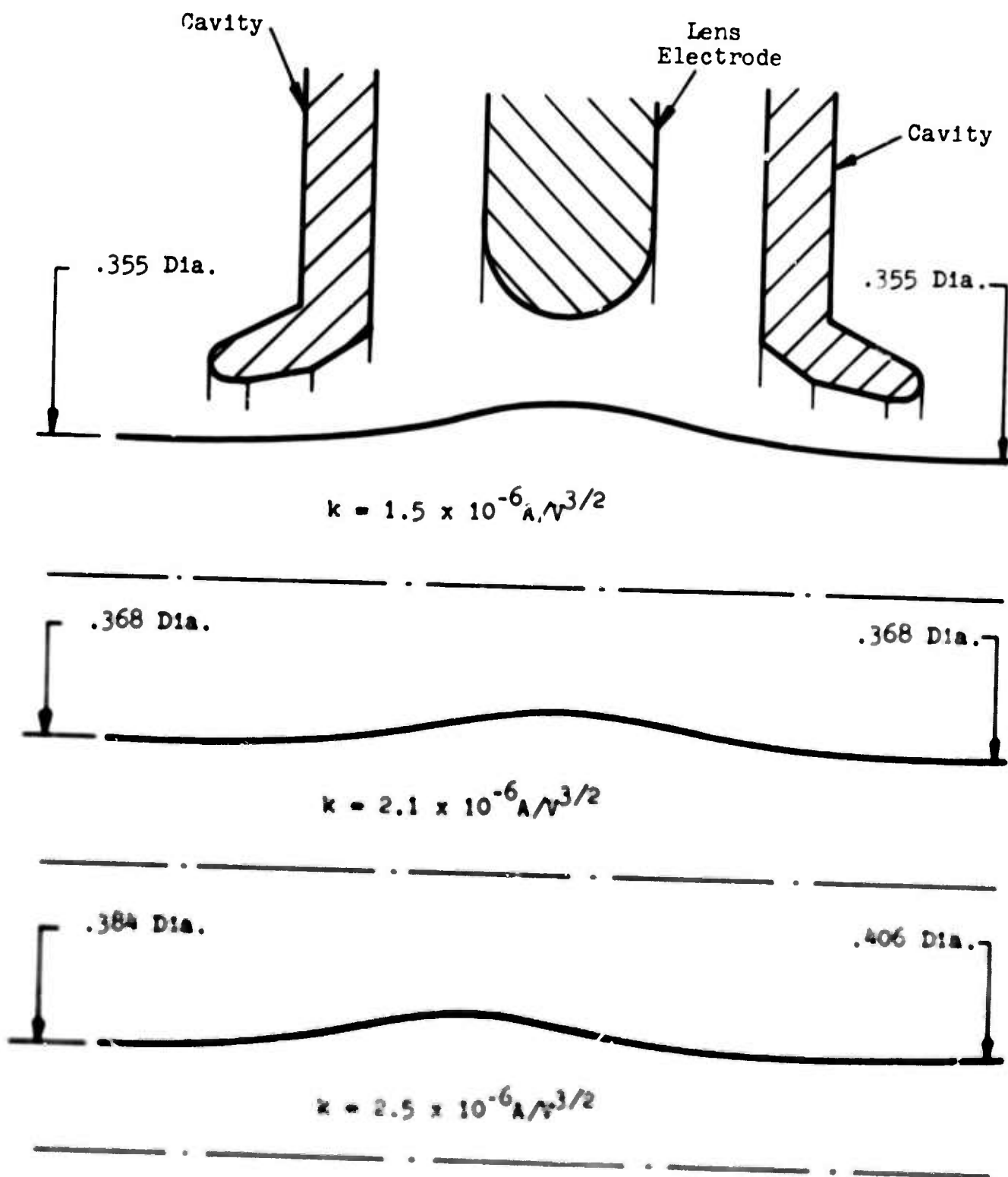
1.3 FURTHER STUDIES WITH THE FOCUSING STRUCTURE

Since the tube is intended to be operated at beam perveances of up to $2.5 \times 10^{-6} \text{ A/V}^{3/2}$, it was decided to check the lens system, which was optimized for a perveance of $1.5 \times 10^{-6} \text{ A/V}^{3/2}$, at this highest operating perveance. In Fig. 7 the trajectories for perveances between 1.5×10^{-6} and



CATHODE TEMPERATURE VS FILAMENT POWER
L-5114 No. 1

Fig. 6



ELECTRON TRAJECTORIES FOR A 1.5, 2.1, and
 $2.5 \times 10^{-6} A/V^{3/2}$ PENNING LENS SYSTEM

Fig. 7

$2.5 \times 10^{-6} \text{ A/V}^{3/2}$ are shown. These trajectories were calculated by using the Litton Resistance Network Analogue in conjunction with a high speed digital computer. As can be seen from that figure, at a perveance of $2.5 \times 10^{-6} \text{ A/V}^{3/2}$, the electrons do not quite come back to their original diameter, which may indicate that the system might not be too stable at this high perveance level. In the following table, the voltage depressions on the axis under the focusing lens are given for different perveances:

PERVEANCE $k \times 10^{-6} \text{ A/V}^{3/2}$	VOLTAGE DEPRESSION %
1.5	53.3*
2.1	55 *
2.5	56 *

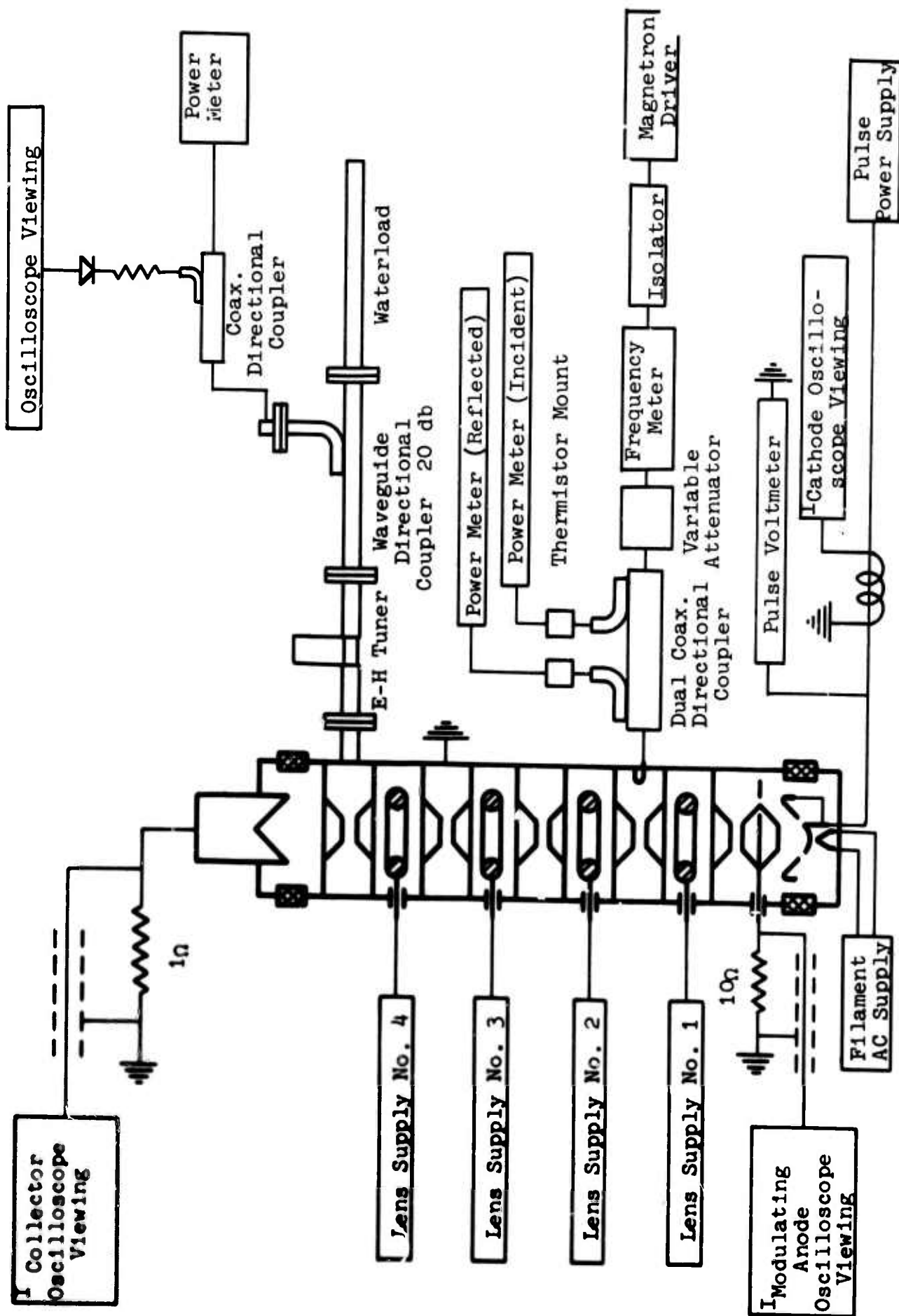
* These values are true for any applied lens voltage in any of the three individual cases.

1.4 PRELIMINARY HOT TEST RESULTS

Figure 8 shows a schematic of the test setup for preliminary testing of the tube. As one can see, each lens is tied to a separate dc power supply. This allows greater flexibility in optimizing the beam focusing during testing.

Also, it can be seen that the modulating anode is tied to ground over a 100 noninductive resistor, which allows viewing of any intercepted current.

During this report period, the tube was tested only up to 25 kV (design voltage 40 kV). An E-H tuner was used between tube output circuit and load circuit in order to



SCHEMATIC DIAGRAM L-5114 ESK TEST CIRCUIT

Fig. 8

match the output coupling at these low operating voltages. The tuning range of the tube was measured to be approximately 80 MHz between 3009 and 3089.5 MHz. Figure 9 shows the rf output power vs cathode voltage. The perveance was $1.73 \times 10^{-6} \text{ A/V}^{3/2}$.

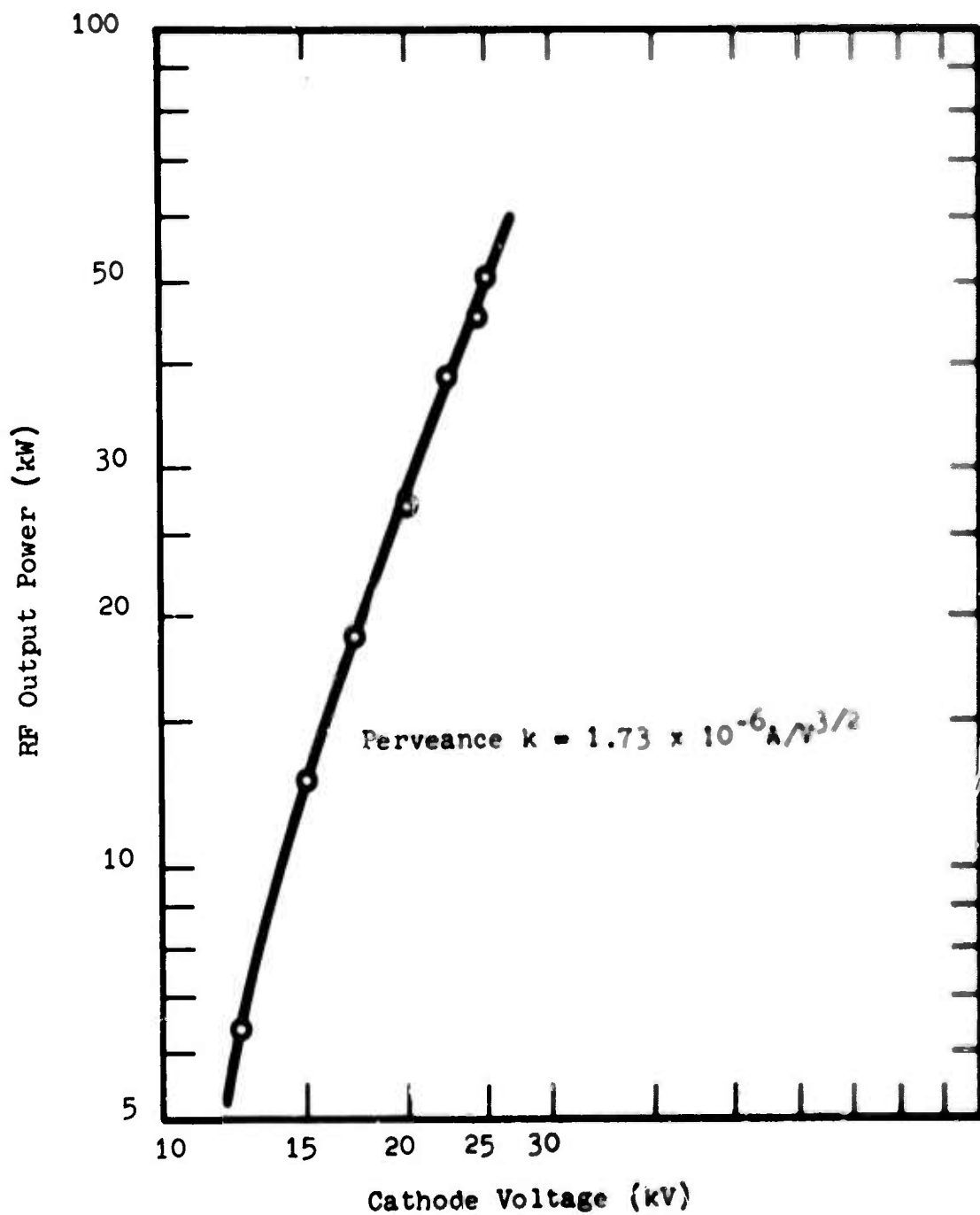
RF output as a function of rf drive power is shown in Fig. 10. The beam voltage was 25 kV and everything including lens voltages, cavity tuners and E-H tuner were optimized for each drive level. For the second curve, the tuning was held fixed, and it showed the typical klystron drive characteristic.

In the next picture, Fig. 11, the efficiency and beam transmission vs perveance can be seen. For these data, the tube was operated at 25 kV. The perveance was varied by changing the cathode filament power. These data clearly demonstrate that by going higher in perveance, one will loose some efficiency. This is also observed in the conventional magnetically-focused klystrons.

1.5 EVALUATION OF A TRIPLE-GAP EXTENDED INTERACTION OUTPUT CAVITY IN C-BAND

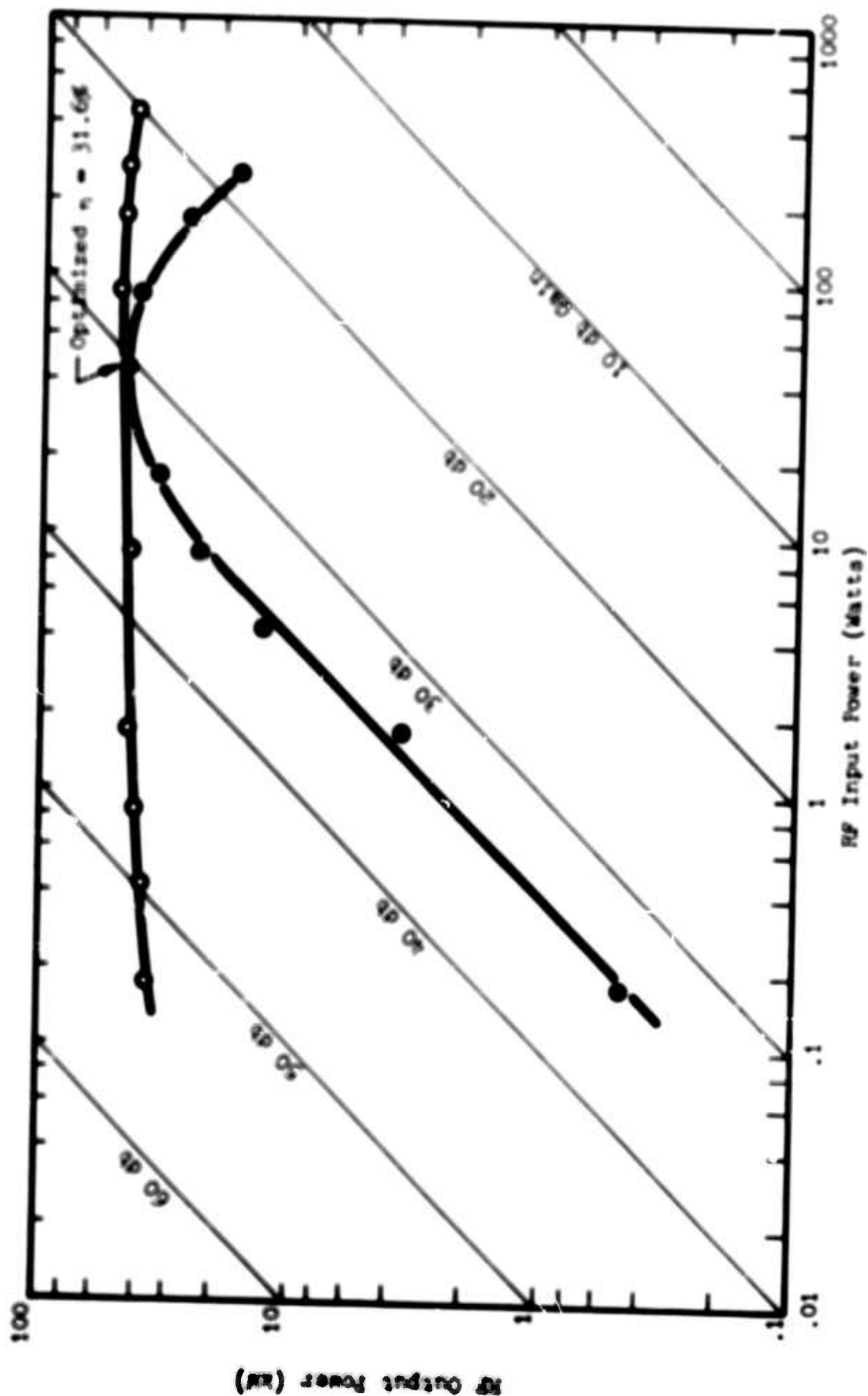
The eventual goal of this program is to study the feasibility of a high power, broadband, C-band ESFK. Therefore, some theoretical work has been done on focusing a 2.5 MW beam through a C-band triple gap extended interaction output cavity. In this study we used the Litton Resistance Network Analogue in combination with a high speed digital computer. The following design objectives were assumed:

Frequency	5500 MHz
RF Output power	1 Mw
P_{beam}	2.5 Mw
Efficiency	40%
Perveance	$2 \times 10^{-6} \text{ A/V}^{3/2}$



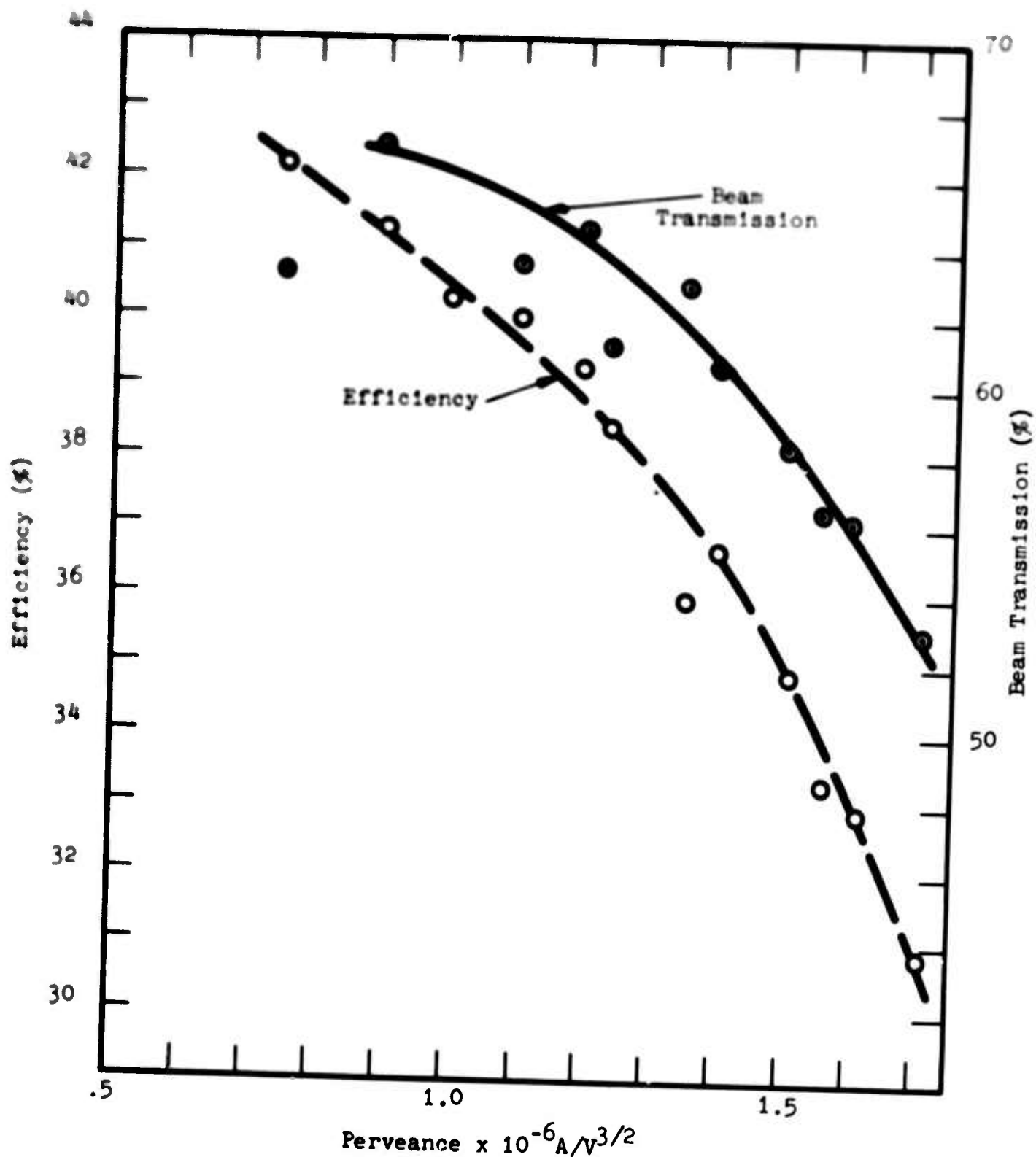
RF OUTPUT POWER VS CATHODE VOLTAGE
L-5114 NO. 1

Fig. 9



RF OUTPUT POWER VS DRIVE POWER, L-5111 NO. 1
 $V_k = 25 \text{ kV}$, $f = 3040 \text{ MHz}$, $k = 1.52 \times 10^{-6} \text{ A/V}^{3/2}$

FIG. 10



EFFICIENCY AND BEAM TRANSMISSION VS PERVEANCE
 L-5114 NO. 1
 $V_k = -25 \text{ kV}$

Fig. 11

Drift Angle	γd	.7*
Transit Angle	γd	.7

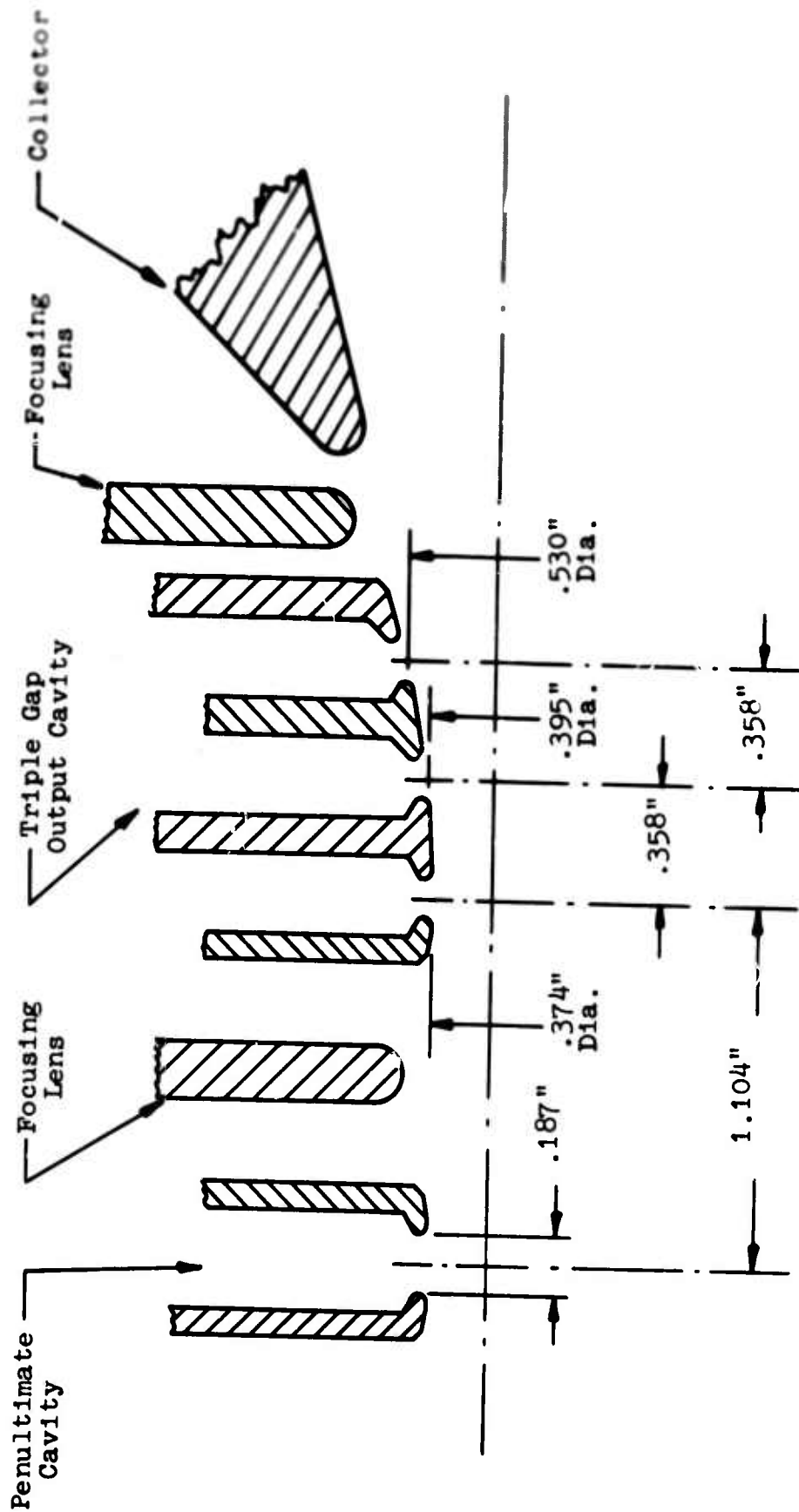
With these assumed values, the following data could be calculated:

V_{beam}	69 kV
I_{beam}	36.2 Amps
$\gamma_{\text{relativistic}}$	2.42 cm^{-1}
l	.91 cm
d	.29 cm

As can be seen, the length of this triple-gap section is rather long for focusing a high-perveance beam through. Since it is undesirable to use focusing lenses within a triple gap output cavity, it becomes necessary to taper the drift tube corresponding to the beam spread curve. Also, a focusing lens was then placed between cavity and collector, as can be seen in Fig. 12.

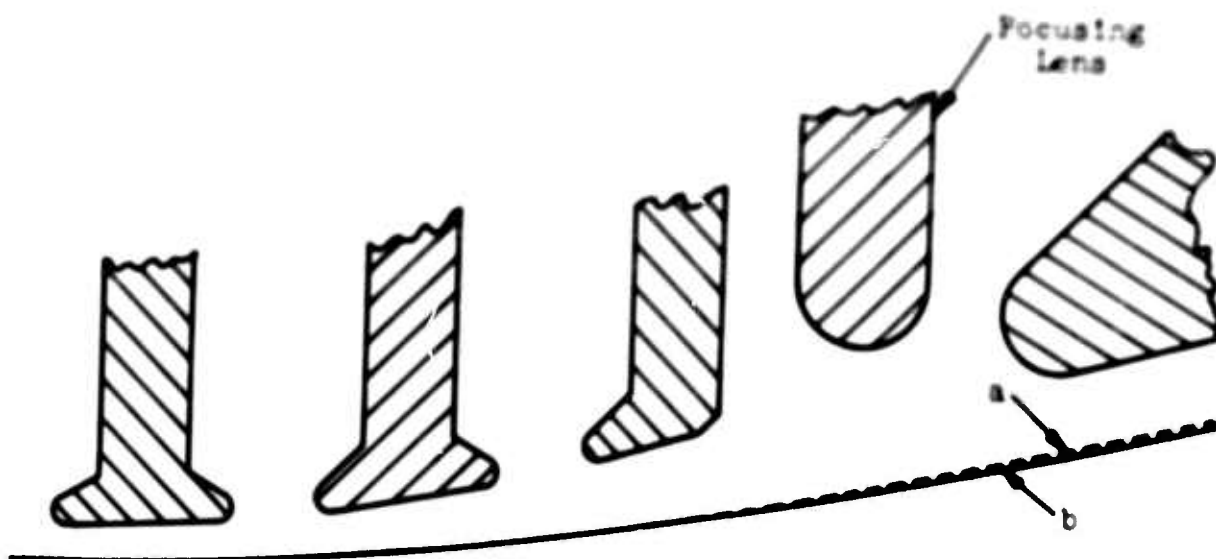
Several runs were made and are described in the following section.

Figure 13 shows the beam trajectories under dc conditions and compares the cases where the lens is at body potential (ground) and on +10 kV above ground. It is obvious that the lens does not have much focusing effect. The next figure, No. 14, shows the same cavity configuration, but the beam trajectories are under rf conditions. For these cases, a beam perveance twice as high as that under dc conditions was assumed. Here three different cases are shown. First the lens is on body (ground) potential, second the lens is on +10 kV, and third the lens is at -20 kV with regard to body voltage.



SKETCH OF TRIPLE GAP EXTENDED INTERACTION
C-BAND OUTPUT CAVITY

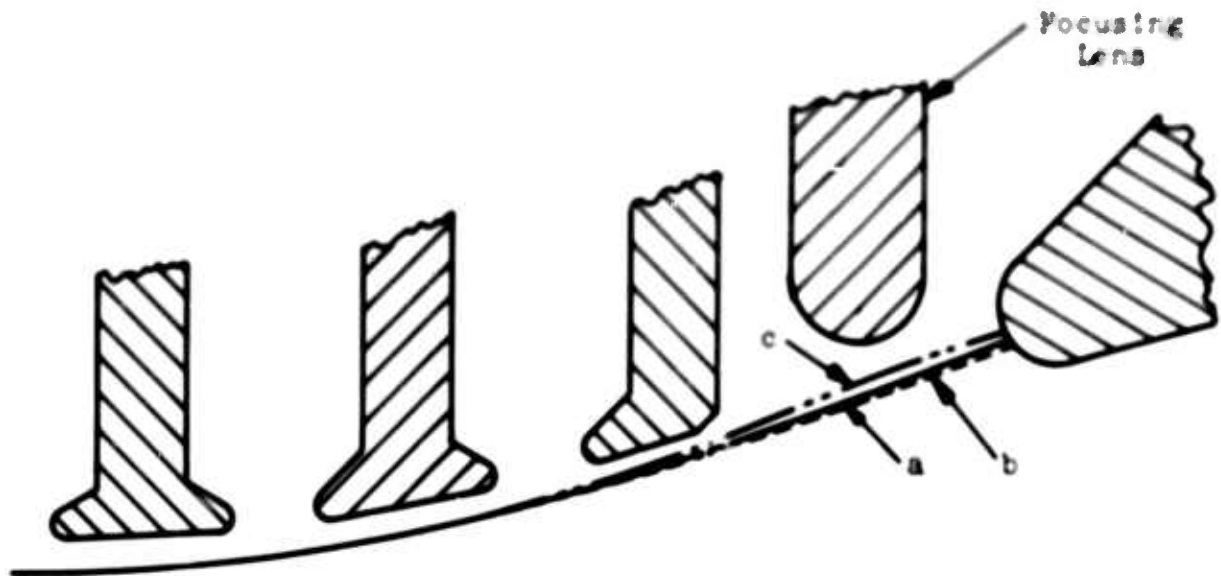
Fig. 12



- a - Lens at Body Potential (Ground)
b - Lens at +10 kV

ELECTRON TRAJECTORIES UNDER DC CONDITION
FOR TRIPLE GAP OUTPUT CAVITY

Fig. 13



-
- a - Lens at Body Potential (Ground)
 - b - Lens at +10 kV
 - c - Lens at -20 kV

ELECTRON TRAJECTORIES UNDER RF CONDITIONS
FOR TRIPLE GAP OUTPUT CAVITY

Fig. 14

1.6 BEAM POWER AND PERVEANCE LIMITS FOR ELECTROSTATICALLY FOCUSED KLYSTRONS

A fundamental requirement for periodic electron beam focusing systems is that there exists a maximum permissible axial spacing between lenses, which cannot be exceeded without resulting in beam blow-up. An excellent insight into this requirement has been given by Pierce.¹ He considers a sequence of thin electron lenses, separated by an axial spacing L , through which an electron beam flows. (Pierce's Fig. 11.6). In the plane of the lens the electron beam has a radius r_0 and, in that plane, each electron receives a radial impulse toward the axis of symmetry due to the action of the lens field. Between lenses, the only dc forces acting on the beam are those due to its own space-charge, which causes it to spread.

Pierce's Fig. 9.2 shows the beam spread action as predicted by the "universal beam spread" equation. This figure illustrates the fact that there exists a maximum axial distance beyond which the beam cannot travel without exceeding its original radius. If the radius is not to be allowed to grow larger, then another lens must be placed at this maximum distance. Pierce's Fig. 11.8 shows the initial negative slope required to cause an electron beam to return to its original radius as a function of distance between lenses. The maximum distance expressed in normalized units is 2.16. This may be stated as:

$$\left(\frac{.174}{r_0} \sqrt{k} \right) L \leq 2.16$$

¹ J.R. Pierce, "Theory and Design of Electron Beams," D. VanNostrand, 1954, pp. 194-207.

where: k = beam microperveance

r_0 = beam radius at lens

L = spacing between lenses

This expression is valid provided the lenses are thin and have no spherical aberrations. This is not true in practice. In addition, when a density-modulated electron beam must be focused by such a lens system, the effective microperveance may be up to twice the value for a dc beam. The expression for the maximum lens spacing for an electrostatically focused klystron will be assumed to be:

$$\left(\frac{.174 \sqrt{k}}{r_0} \right) L = 1.5$$

It is now instructive to express the maximum lens spacing in terms of klystron design parameters. The beam radius r_0 at the lens plane can be expressed in terms of the normalized klystron gap radius γa and the electron wave number. (Relativistic effects are ignored).

$$r_0 = \left(\frac{r_0}{a} \right) (\gamma a) \left(\frac{1}{\gamma} \right)$$

where: a = gap radius

$$\gamma = \frac{\omega}{\mu_0} = \left(\frac{2\pi}{\lambda} \right) \left(\frac{506}{V_0^{1/2}} \right)$$

V_0 = dc beam voltage

λ = free-space wavelength

The dc beam voltage is related to the dc beam power, W_0 and the beam microperveance k as follows:

$$V_o^{\frac{1}{2}} = \left(\frac{10^9 W_{okw}}{k} \right)^{1/5}$$

Substituting for $V_o^{\frac{1}{2}}$:

$$\gamma = \left[\frac{(2\pi) (506) (10)^{1/5}}{10^2} \right] \frac{k^{1/5}}{\lambda W_{okw}^{1/5}} .$$

Substituting for γ :

$$r_o = \left[\frac{10^2}{(2\pi) (506) (10)^{1/5}} \right] \frac{\lambda W_{okw}^{1/5}}{k^{1/5}} (\gamma a) \left(\frac{r_o}{a} \right) .$$

Substituting for r_o in the maximum lens spacing expression:

$$\left[\frac{(0.174) (2\pi) (506) (10)^{1/5}}{10^2} \right] \frac{k^{1/5} \sqrt{k}}{W_{okw}^{1/5} (\gamma a) \left(\frac{r_o}{a} \right)} \left(\frac{L}{\lambda} \right) = 1.5$$

For a typical klystron design, the product of $\frac{r_o}{a}$ and γa would be very close to unity. Therefore, by assuming $\left(\frac{r_o}{a} \right) (\gamma a) = 1.0$, the maximum lens spacing relation becomes:

$$\frac{L}{\lambda} = (.171) \frac{W_{okw}^{1/5}}{k^{7/10}}$$

Figure 15 is a plot of the maximum permissible axial lens spacing normalized by the free-space wavelength, vs peak beam power, with microperveance as a parameter. It may be observed that the choice of electron beam microperveance has a pronounced effect on the maximum permissible lens spacing.

Having determined the maximum lens spacing as a function of beam power, microperveance, and wavelength, it is now possible to determine the ultimate limits of ESFK design. Figure 16 depicts the cavity-lens configuration of an ESFK. The spacing between lenses must allow for a lens electrode of thickness T , two high voltage gaps of width S , two cavity walls of thickness w , and a cavity resonator of height H . The lens spacing may be expressed as:

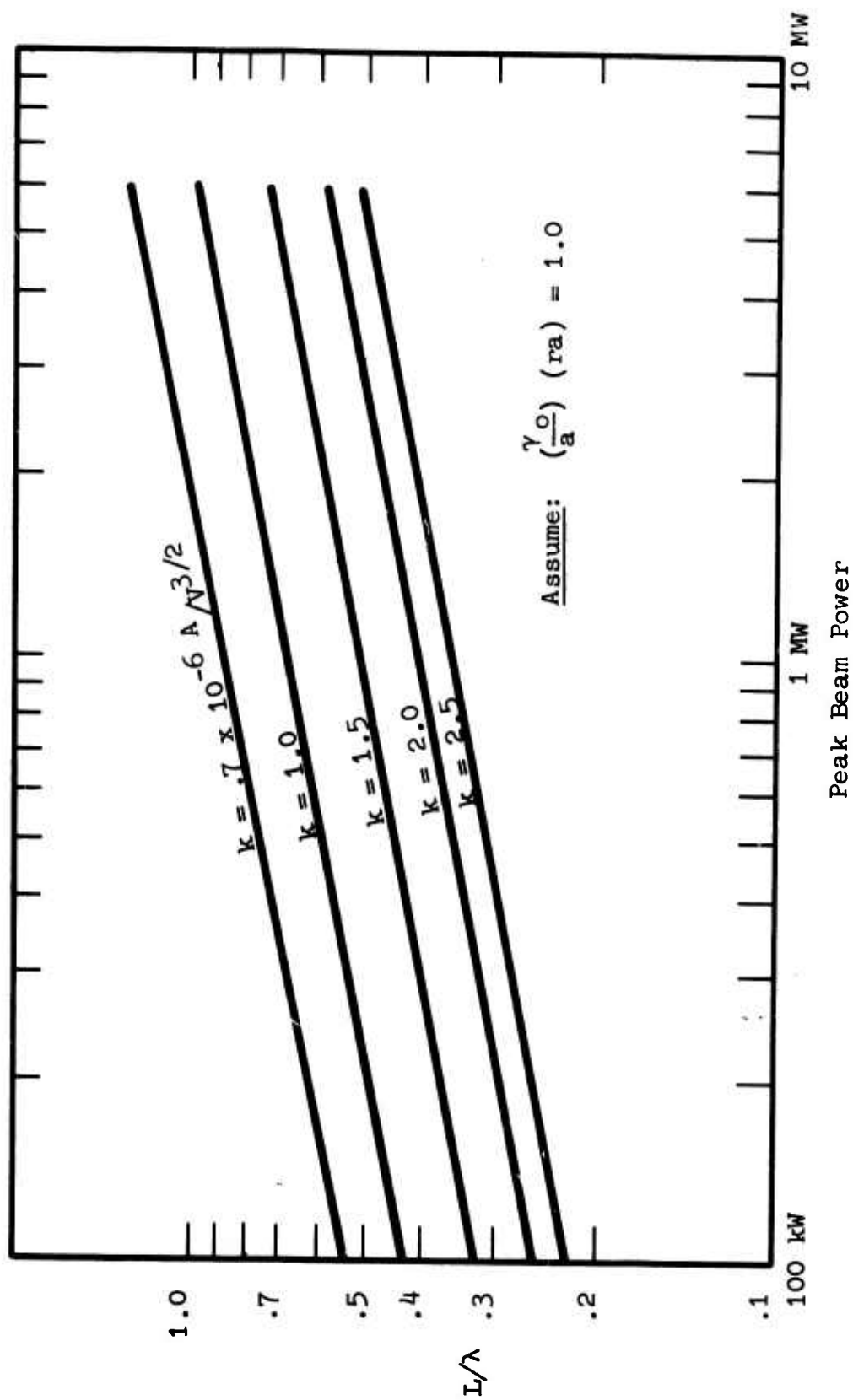
$$L = 2 (S + w) + T + H \quad .$$

The lens-gap spacing depends upon the operating voltage, which will be assumed equal to the beam voltage, and the allowable voltage gradient. For a maximum voltage gradient of 118 kV/cm (300 v./mil.):

$$S = \frac{1}{29.8} \left(\frac{W_0}{k} \right)^{2/5} \quad .$$

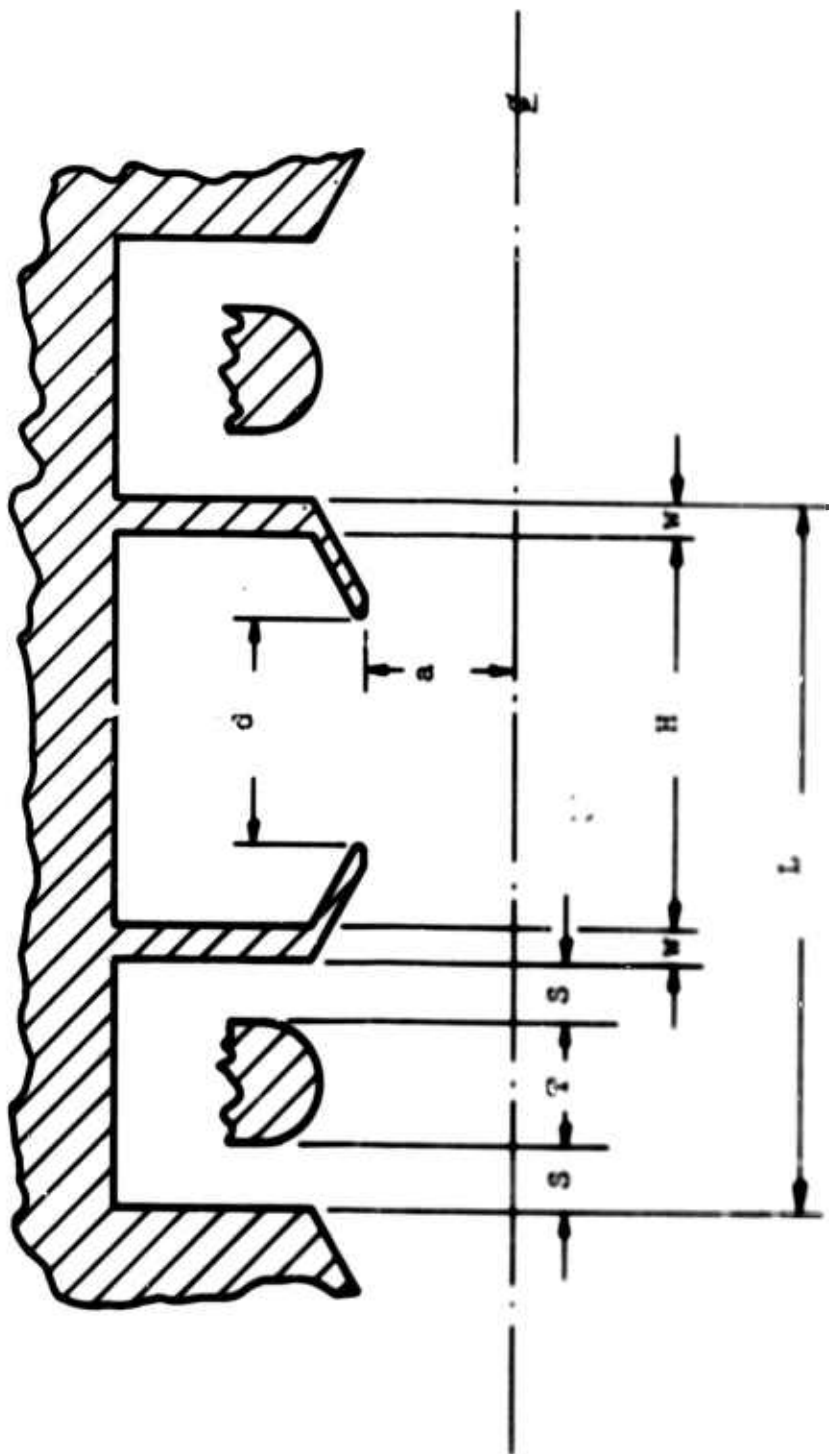
A typical cavity gap transit angle, γ_d , would be 1.1 radians. For reasonable values of R/Q , the cavity height should not be less than $2 \gamma_d$. Therefore, the assumption of $H = 2 \gamma_d$ is made, or:

$$H = \frac{2.2\lambda}{50.4} \left(\frac{W_0}{k} \right)^{1/5} \quad .$$



MAXIMUM NORMALIZED LENS SPACING VS
 BEAM POWER FOR ELECTROSTATICALLY FOCUSED KLYSTRON

Fig. 15



CAVITY-LENS CONFIGURATION

FIG. 16

The lens electrode thickness may be approximated by assuming that its radius of curvature should be no less than $5/2$ in order to prevent excessive local electric field gradients. Therefore, it is assumed that $T = 5$.

The minimum cavity wall thickness, W , is not easy to specify because it depends on the cavity diameter and the average power of the klystron. The following values will be used in the analysis which follows:

$$w = .03 \lambda \quad \text{at } 10 \text{ cm}$$

$$w = .04 \lambda \quad \text{at } 5 \text{ cm}$$

$$w = .06 \lambda \quad \text{at } 3 \text{ cm.}$$

The minimum lens spacing may now be expressed as:

$$L = 3S + 2\gamma d + 2w$$

or

$$L = .1 \left(\frac{V_0}{k} \right)^{2/5} + .0436 \lambda \left(\frac{V_0}{k} \right)^{1/5} + 2w$$

where: $w = .03$ at $\lambda = 10 \text{ cm}$

$w = .04$ at $\lambda = 5 \text{ cm}$

$w = .06$ at $\lambda = 3 \text{ cm.}$

Normalizing with respect to free-space wavelength:

$$L/\lambda = \frac{1}{\lambda} \left(\frac{V_0}{k} \right)^{2/5} + .0436 \left(\frac{V_0}{k} \right)^{1/5} + 2w$$

This expression was solved for various values of peak beam power and microperveance at wavelengths of 10 cm, 5 cm, and 3 cm. The values of normalized maximum lens spacing are plotted along with the values of minimum lens spacing in Figs. 17 through 20. Where the two curves intersect determines the maximum beam power limit for an ESPK for a given microperveance and wavelength. Similarly, the maximum beam microperveance for an ESPK may be determined for a given peak beam power and wavelength.

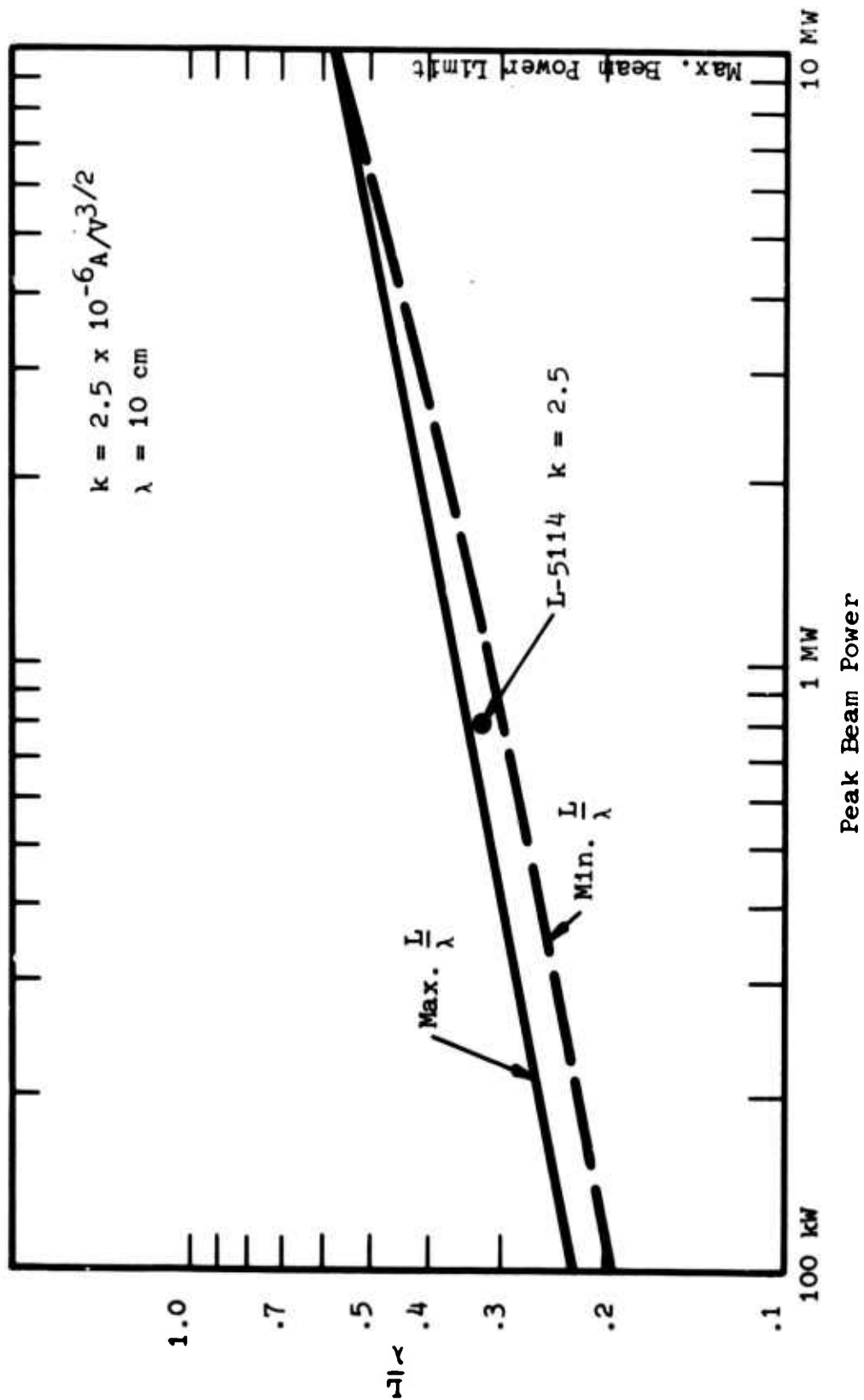
An expression for the maximum microperveance and/or maximum peak beam power for an ESPK at a given wavelength may be obtained by equating the expressions for maximum and minimum lens spacings.

$$.171 \frac{W_o}{k^{.7}} \frac{1}{K^{1/5}} = \frac{1}{\lambda} \left(\frac{W_o}{K} \right)^{2/5} + .0436 \left(\frac{W_o}{K} \right)^{1/5} + 2N$$

Examination of Fig. 17 indicates the maximum beam microperveance for high power klystrons in S-band to be equal to, or greater than, 2.5. Figure 18 indicates that megawatt klystrons are feasible in C-band with microperveance 1.0 beams. Increasing the microperveance to 1.5 in C-band reduces the feasible klystron power level, as seen in Fig. 19. At X-band, it is no longer possible to construct a high power ESPK with a desirable beam microperveance. Figure 20 indicates a maximum beam power limit of 650 kW for a 0.7 microperveance beam at 3 cm.

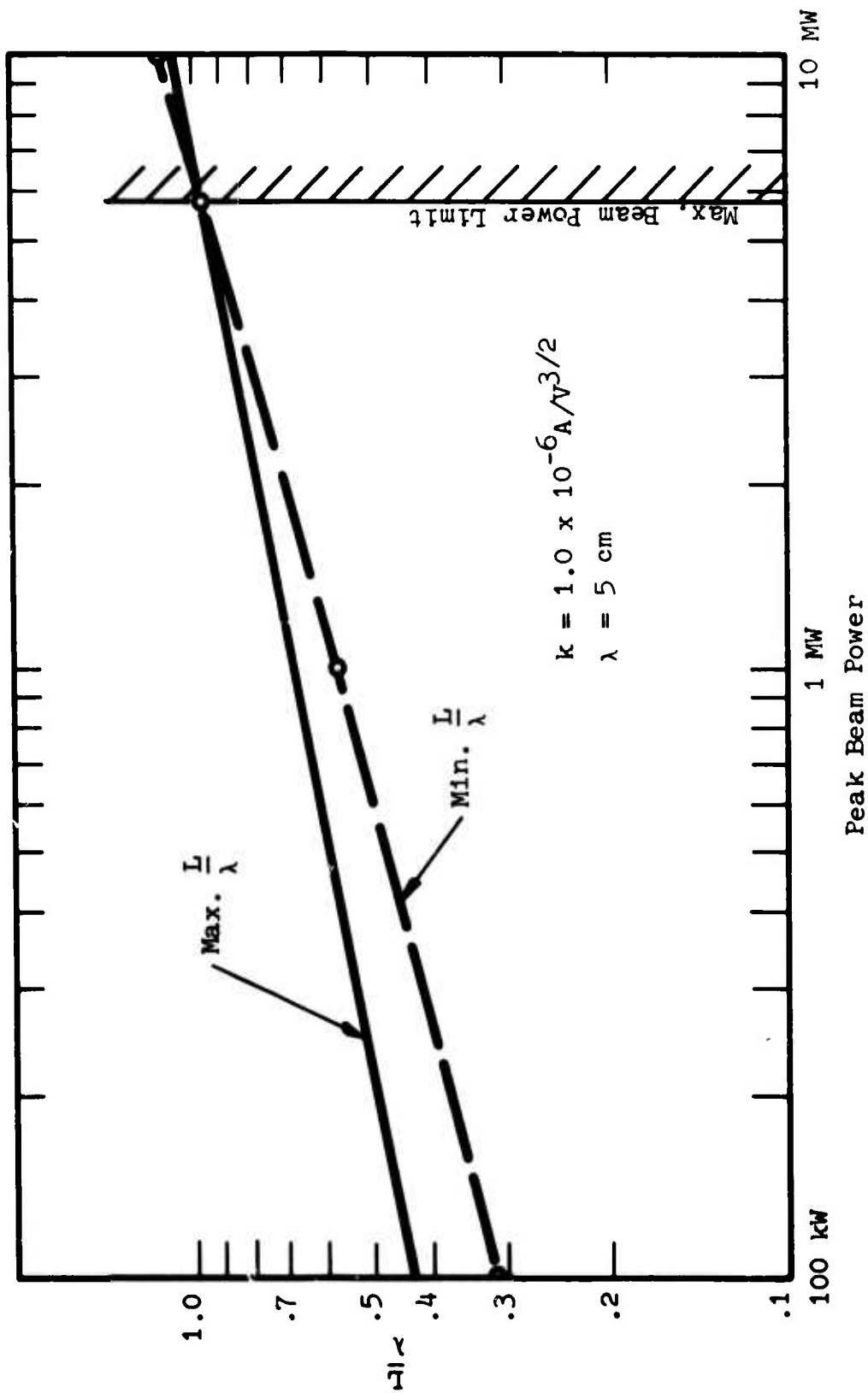
The limitation of beam perveance with frequency implies a limitation on the klystron bandwidth since it can be shown that bandwidth is directly proportional to $k^{4/5}$.

This analysis of beam power and perveance limits for the ESPK is, of necessity, based on many assumptions whose



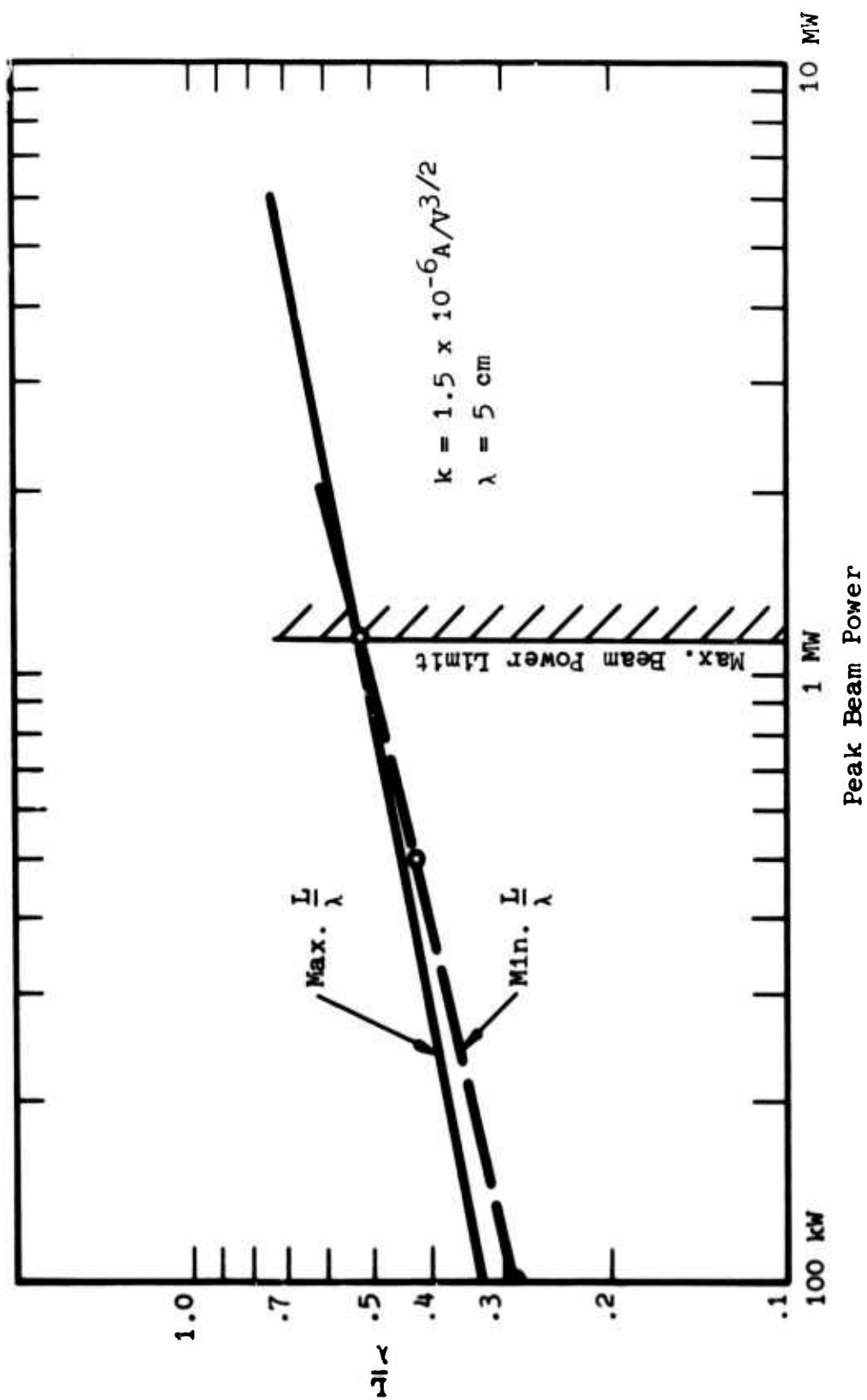
MAXIMUM AND MINIMUM NORMALIZED LENS SPACING
 VS BEAM POWER FOR ELECTROSTATICALLY FOCUSED KLYSTRON

Fig. 17



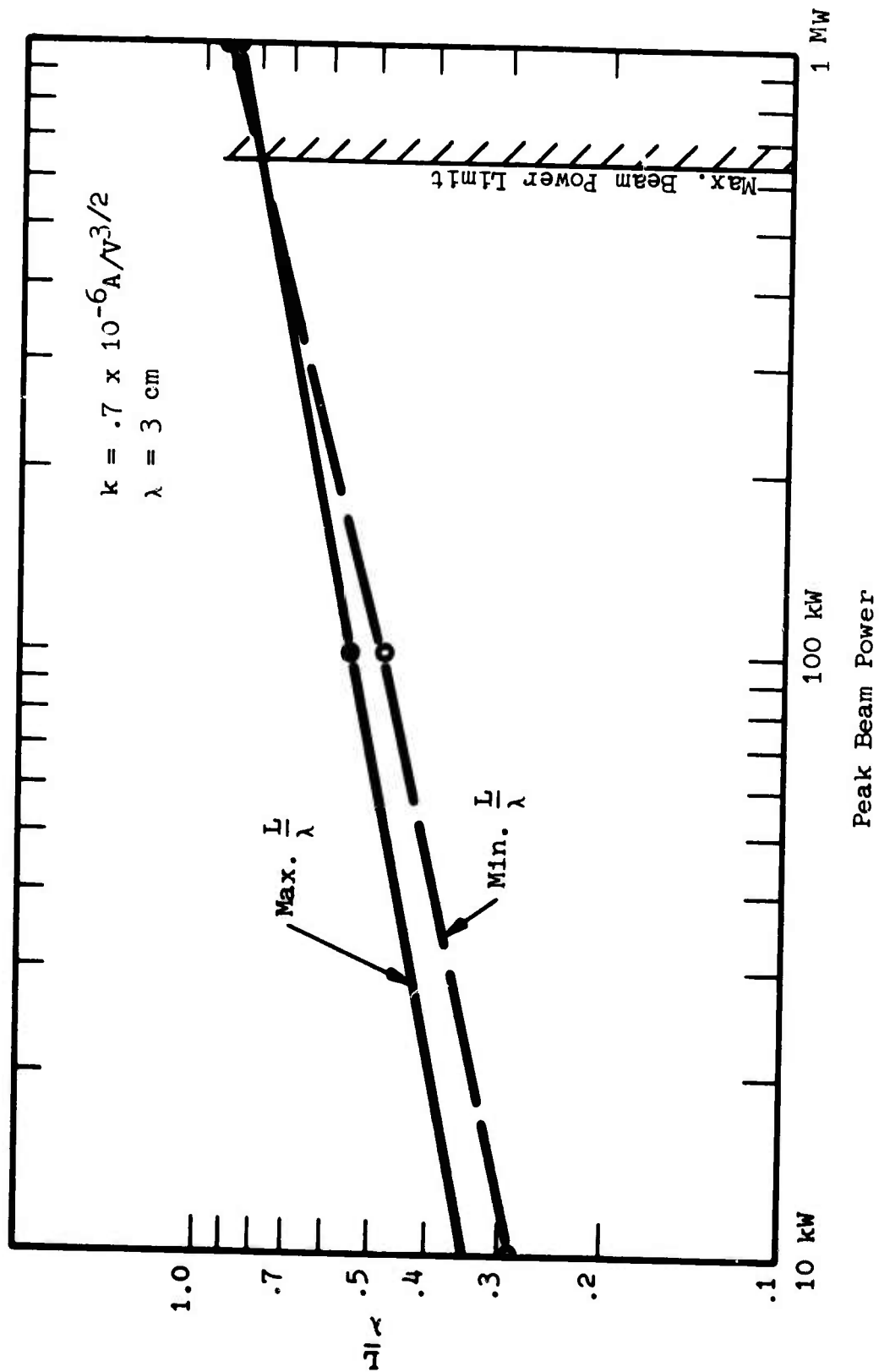
MAXIMUM AND MINIMUM NORMALIZED LENS SPACING
 VS BEAM POWER FOR ELECTROSTATICALLY FOCUSED KLYSTRON

Fig. 18



MAXIMUM AND MINIMUM NORMALIZED LENS SPACING
 VS BEAM POWER FOR ELECTROSTATICALLY FOCUSED KLYSTRON

Fig. 19



MAXIMUM AND MINIMUM NORMALIZED LENS SPACING
 VS BEAM POWER FOR ELECTROSTATICALLY FOCUSED KLYSTRON

Fig. 20

validity is open to question. The assumption of $(r_0/a)(\gamma a) = 1.0$ is very conservative; whereas, the assumption of $T = S$ is not conservative. Practical considerations such as voltage breakdown, body cooling, and cavity conductance requirements will doubtless alter the limits defined herein. However, it is hoped that this analysis will provide a useful "ballpark" estimate of the ultimate limits of the ESK.

2.0 SUMMARY AND CONCLUSIONS

1. The experimental tube was assembled and successfully exhausted.
2. The gun was preglowed in a bell jar.
3. Hot test of the experimental tube has been started. Obtained results look promising.
4. The focusing lens system was checked at a perveance of $2.5 \times 10^{-6} \text{ A/V}^{3/2}$ by means of the Litton Network Analogue and the high speed digital computer. At this high perveance level, the system may not be too stable any more.
5. Theoretical studies on a triple gap extended interaction output cavity have been started. This cavity was scaled for operation at C-band.
6. Studies on beam power and perveance limits for ESFK's have been made.

3.0 PROGRAM FOR NEXT QUARTER

1. Test setup will be made to test tube up to the design voltage of 40 kV and to be able to change the modulating anode voltage from 32 kV to 56 kV with respect to cathode.
2. Further hot test with experimental tube will be made.
3. The theoretical studies with the triple gap extended interaction output cavity will be continued.

4.0 ADMINISTRATIVE INFORMATION

The number of scientific and engineering manhours expended during the reporting period are as follows:

Dr. G. E. Pokorny	123	Hours
Mr. W. R. Day	12	Hours
Mr. T. H. Luchsinger	179.5	Hours
Mr. C. K. Whittaker	160	Hours
Mr. A. H. Zanotti	54	Hours
Mr. E. K. Shaw	8	Hours
Total	536.5	Hours

On October 10, 1966, Mr. Park Richmond, ECOM Project Engineer, visited this facility. The overall program plan for the subject contract and details of the technical approach for the future were discussed between him and Messrs. H. Luchsinger and G. Pokorny of the Research Department.

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13. ABSTRACT The L-5114 Experimental electrostatically-focused klystron with variable beam perveance has been assembled and successfully exhausted without any major problems. Further work with the resistance network analogue has been done to check the lens system on the extreme high side ($k=2.5 \times 10^{-5} \text{ A/V}^{3/2}$) of the variable beam perveance. Hot test of the tube has been started and the initial results obtained look promising. Studies on a triple-gap extended interaction cavity have been made. This cavity is scaled to C-band and the assumed perveance is $2.0 \times 10^{-6} \text{ A/V}^{3/2}$. Also some studies on beam power and perveance limits for electrostatically focused klystrons as functions of operating frequency have been made.			

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