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TECHNICAL REPORT ECOM-02253-1

STUDY OF HIGH-POWER ELECTROSTATICALLY FOCUSED KLYSTRONS

FIRST QUARTERLY PROGRESS REPORT

By

T. H. Luchsinger - G. E. Pokorny

November 1966

Sponsored by:

Advanced Research Projects Agency
Project Defender - OSD, ARPA Order No. 436

ECOM

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

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

LITTON INDUSTRIES
ELECTRON TUBE DIVISION
960 INDUSTRIAL ROAD · SAN CARLOS, CALIFORNIA

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STUDY OF HIGH-POWER ELECTROSTATICALLY FOCUSED KLYSTRONS

QUARTERLY REPORT NO. 1

Contract No. DA 28-043-AMC-02253 (E)
Signal Corps Technical Guidelines
MW-7B, 3 February 1966

FIRST QUARTERLY PROGRESS REPORT
1 May 1966 to 31 July 1966

November 1966

Prepared by:

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Under the Direction of:

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"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."

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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 X bandwidth and efficiency X 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 $2.5 \times 10^{-6} A/V^{3/2}$
Gun perveance	$1.5 \times 10^{-6} Amp/V^{3/2}$.

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

A periodic electrostatic focusing structure optimized for a beam perveance of 1.5×10^{-6} has been designed utilizing the resistor network analogue in conjunction with a digital computer. The lens electrodes are at cathode potential and are located between each cavity. Also a 1.5×10^{-6} perveance gun was designed with the resistor network. The same gun was checked by applying different modulating anode voltages.

Buncher and output cavity models have been built and cold-tested. The design of the experimental tube has been completed and parts have been ordered.

1.0 FACTUAL DATA

1.1 INTRODUCTION

The present program, a continuation of the study of high-power electrostatically focused klystrons was started on May 1, 1966. The primary goal of this eight-month program is to investigate the feasibility of employing higher perveance beams 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	$1.5 \times 10^{-6} A/V^{3/2}$
Beam perveance	Variable between 1.0×10^{-6} and $2.5 \times 10^{-6} A/V^{3/2}$
Modulating anode voltage	Variable between 30 and 56 kv
Beam current	Variable between 8 and 20 amps.
RF pulse length	10 μs
Duty	.001
Gain	36 db

This report will first discuss the general approach to the objectives of this program, then specific areas, such as the design of the focusing system, the gun design, and cold test of buncher and output cavity will be discussed in detail.

1.2 TECHNICAL DISCUSSION

This program is an essential phase in the investigation of approaches leading to increased bandwidth and power output in existing high-power electrostatically focused klystron amplifiers. The results will help to determine the feasibility of developing a broadband high-power ESFK amplifier operating in C-Band.

The broadbanding of klystron amplifiers has received considerable attention. Because the basic operating principle of a klystron depends on the use of resonant structures, there are inherent bandwidth limitations on any klystron design.

The bandwidth of a klystron amplifier (see pg. 13) is essentially determined by the R_{sh}/Q of the output circuit with the beam impedance Z_b:

$$\frac{\Delta f}{f} \alpha \frac{R_{sh}}{Q} \frac{1}{Z_b} \quad .$$

The beam impedance Z_b is related to the beam perveance K and the beam power N through the following relation:

$$Z_b = \frac{V_o}{I_o} = \frac{1}{N^{1/5} K^{4/5}} \quad .$$

As one can see from this equation, the beam impedance is a strongly varying function of the beam perveance, but varies much less as a function of the beam power.

Increasing the beam perveance is therefore a crucial design consideration for broadbanding klystrons. A higher beam perveance also has the added advantage of reducing the required beam voltage for a given beam power level. A lower beam voltage is, of course, also attractive for an ESFK amplifier, because it reduces the voltage holdoff gradient in the focusing-lens housing. A lower beam voltage is also desirable from other considerations, such as lower x-ray level, reduced voltage gradients in the gun and gun insulator, and lower insulation requirements in the power supply. The beam voltage V_b, the beam power and the beam perveance are related by:

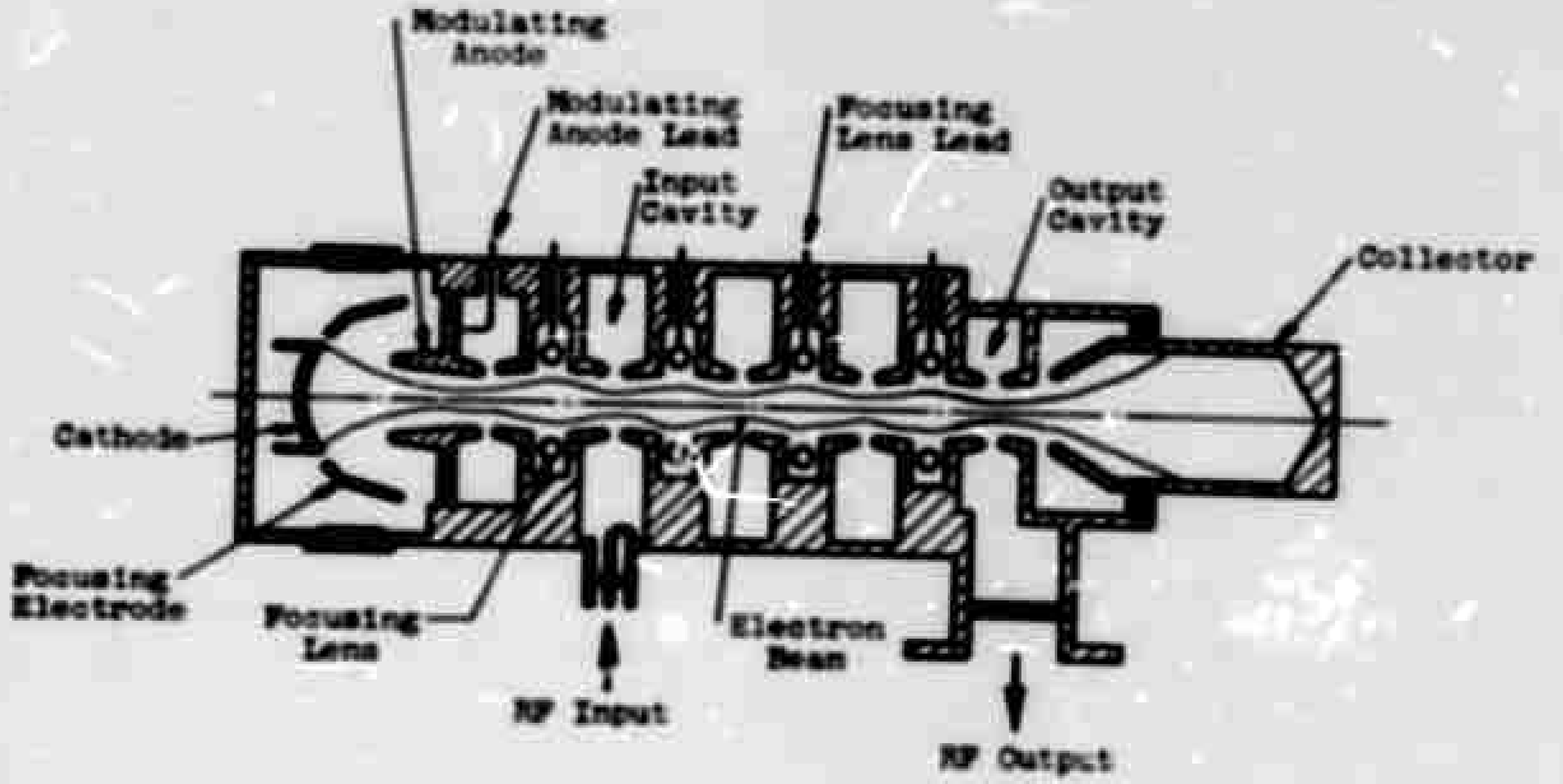
$$V_b = \left(\frac{N}{K}\right)^{2/5}$$

Limitations on the beam perveance are imposed both by the gun design and the focusing system. In conventional magnetically focused klystrons, beam perveance values of up to $3 \times 10^{-6} A/V^{3/2}$ have been successfully used with solid beams.

The highest beam perveance which has been successfully used so far with electrostatic focusing is $1 \times 10^{-6} A/V^{3/2}$. This program will therefore be primarily concerned with an evaluation of the feasibility of using higher beam perveance values in ESFK amplifiers.

1.3 GENERAL DESIGN CONSIDERATIONS

A schematic layout of the tube is shown in Fig. 1. The test vehicle is a modified version of an existing ESFK, the L-3668H. The main difference will be the addition of a modulating anode so that the beam perveance can be changed over a wide range. The design of this experimental tube will be optimized at a beam perveance of $1.5 \times 10^{-6} A/V^{3/2}$. The gun perveance has also been chosen as $1.5 \times 10^{-6} A/V^{3/2}$. Therefore, for a beam perveance of $1.5 \times 10^{-6} A/V^{3/2}$, the modulating anode will be operated at beam potential. The nominal beam voltage is 40 kV and the beam current for a perveance of 1.5×10^{-6} is 12 amperes, correspondingly. In the following table, one can see some of the possible different operating conditions for this tube. This tube will therefore allow a detailed study of the behavior of an ESPK for different beam perveance values.



SCHEMATIC LAYOUT OF THE TUBE

Fig. 1

Gun Perveance (x 10^{-6})	Beam Voltage (kv)	Modulating Anode Voltage Reference to Cathode (kv)	Cathode Current (Amp.)	Lens Voltage (kv)	Beam Perveance (x 10^{-6})	Beam Power (kw)	Expected RF Output (kw)
A. CONSTANT BEAM VOLTAGE							
1.5	40.0	30.5	8.0	40.0	1.0	320	130
1.5	40.0	40.0	12.0	40.0	1.5	480	190
1.5	40.0	50.0	16.8	40.0	2.1	670	270
1.5	40.0	56.0	20.0	40.0	2.5	800	320
B. CONSTANT BEAM POWER							
1.5	46.6	36.0	10.3	46.6	1.0	480	190
1.5	35.9	42.6	13.3	35.9	2.0	480	190
1.5	32.6	46.0	14.75	32.6	2.5	480	190

1.4 ELECTRICAL DESIGN

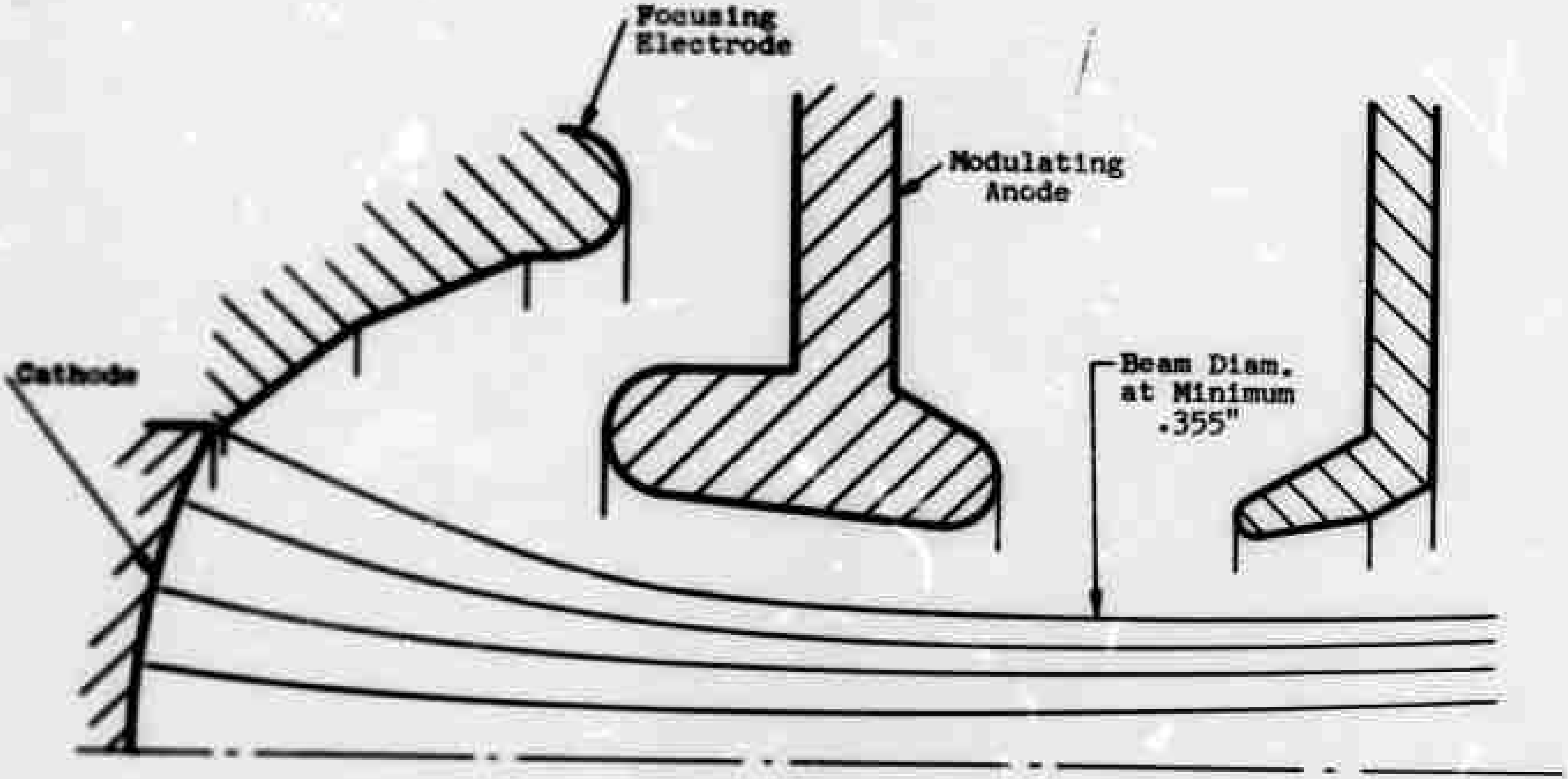
1.4.1 Gun Design

The gun design is a straightforward electrostatically focused Pierce type gun with the following design parameters:

Gun perveance	$1.5 \times 10^{-6} A/V^{3/2}$
(Mod) anode voltage	Variable from 30.5 to 56 kv; 40 kv design center.
Cathode current	Variable between 8 and 20 A 12 amp. design center
Beam power	Variable between 320 and 800 kw.
Cathode diameter	1.97 cm
Cathode area	3.19 cm^2
Cathode half-angle	25^o
Beam diameter (at minimum and 40 kv)	.9 cm
Convergence ratio (area)	5.0

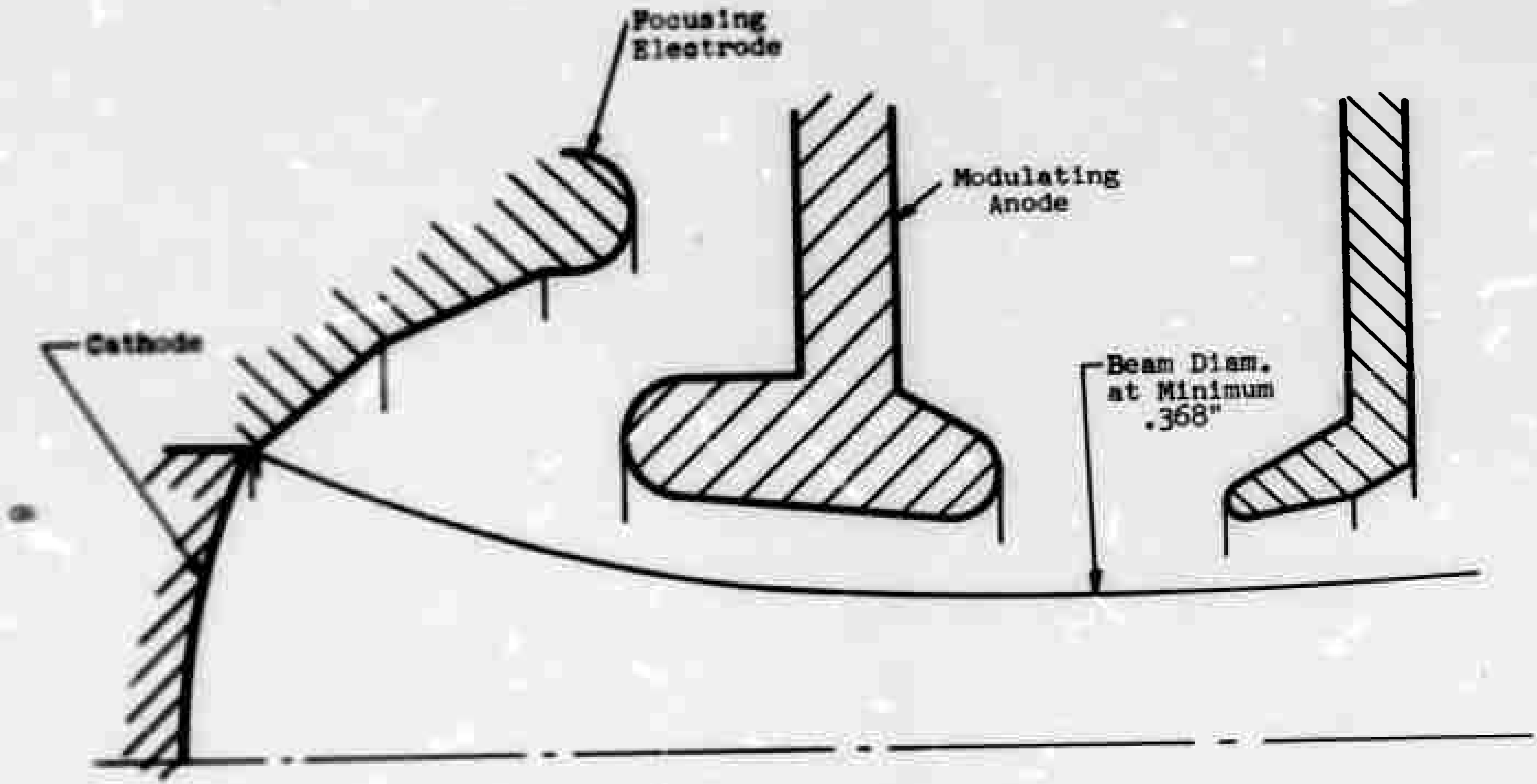
Since this gun will be operated at different mod-anode voltages, it is important for the electrostatic focusing of the beam after it leaves the gun that the location and diameter of the beam minimum does not change much as a function of mod-anode voltage.

Figure 2 shows the electron trajectories for a gun operating at 40 kv (which would yield a 1.5×10^{-6} perv beam). In Fig. 3, the electron trajectories are shown for the gun operating at 50 kv, which would result in a 2.1×10^{-6} perv beam when the body (anode) voltage is at 40 kv. By comparing these two figures, only a negligible difference in minimum beam diameter and axial minimum position can be seen.



ELECTRON TRAJECTORIES AT A CATHODE VOLTAGE OF 40 KV (BEAM PERVEANCE IS 1.5×10^{-6} $A/V^{3/2}$)

Fig. 2



ELECTRON TRAJECTORIES AT A CATHODE VOLTAGE OF 50 KV (BEAM PERVEANCE IS 2.1×10^{-6} $A/V^{3/2}$)

Fig. 3

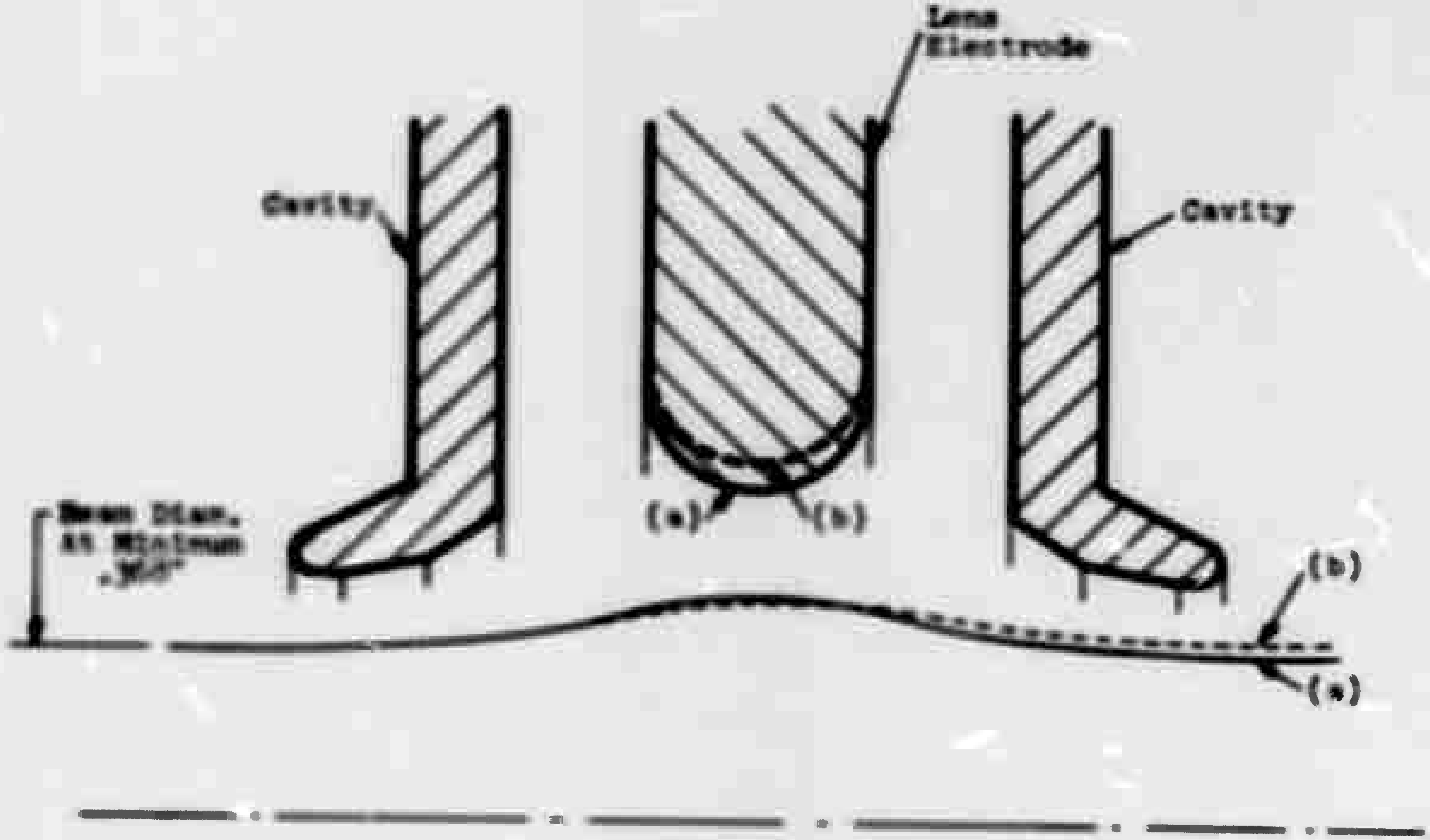
1.4.2 Focusing Structure

The first einzel lens is located between mod-anode and first cavity.

The primary problem here is to develop a lens system which focuses with the lens at or close to cathode potential beams of variable perveance (at least from 1.5 to 2 μ perv) over a fixed lens period and with a minimum of spherical aberration. Of course, the lens system has also to be compatible with good rf interaction and bunching cavity parameters.

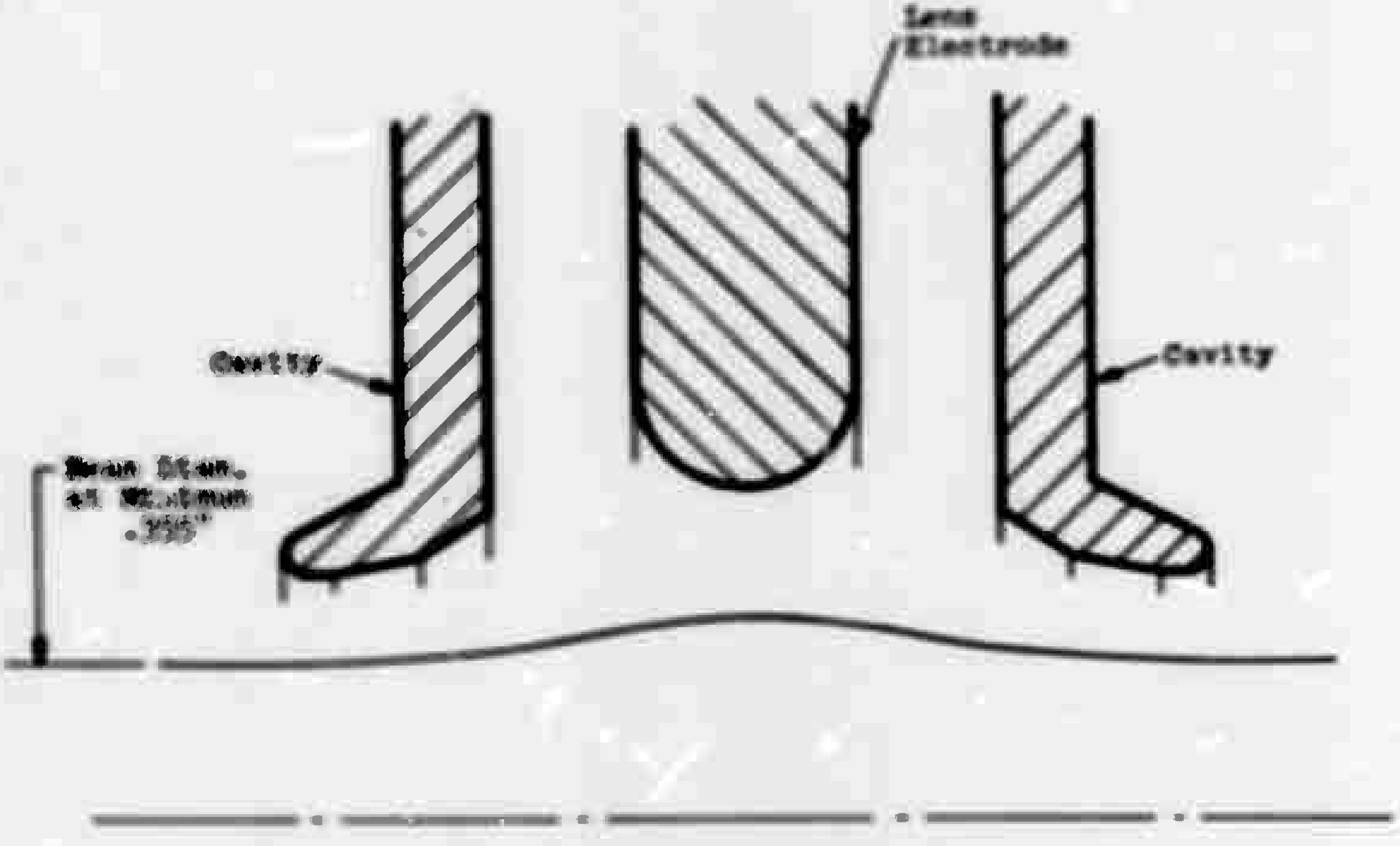
The design of an electron-optically satisfactory lens system, which is consistent with good rf design parameter, has been completed. Plots of the edge trajectories are shown in Figs. 4 and 5. Four such einzel lens systems will be used in this tube with the first system being located adjacent to and upstream of the input cavity. The lens design has been arrived at using the Litton resistance network analogue in conjunction with a high-speed digital computer. In both cases, the lenses ride at cathode potential. Figure 4 shows the trajectories in the lens system when a beam with a beam perveance of 2.1×10^{-6} is injected (this means the modulating anode is at a voltage of 50 kv with reference to the cathode). Electron trajectories are shown for two different lens diameters. As one can see from the drawing, for the smaller lens diameter, the electrons come back to their original diameter after a full period. Therefore, the focusing system will be stable over many periods.

Figure 5 shows geometrically the same system as in Fig. 4, but the beam perveance is changed to 1.5×10^{-6}, which means the modulating anode is at ground (body) potential or at 40 kv with reference to the cathode. Again, the electrons come back to their original diameter after a full period. The significant design parameters for the lens systems are as follows



ELECTRON TRAJECTORIES FOR A 2.1×10^{-6} $A/V^{3/2}$ PERVEANCE LENS SYSTEM

Fig. 4



ELECTRON TRAJECTORIES FOR A 1.5×10^{-6} $A/V^{3/2}$ PERVEANCE LENS SYSTEM

Fig. 5

(at the design center of 1.5×10^{-6} beam perveance):

Focusing period, p	$= 3.25$ cm
Minimum beam diameter, $2b_{min}$	$= .9$ cm
Maximum beam diameter, $2b_{max}$	$= 1.5$ cm
ID of interaction gap, $2a$	$= 1.395$ cm
ID of lens electrode	$= 1.92$ cm
Ratio $\frac{a}{b_{min}}$	$= 1.55$
Propagation constant γ	$= 1.59 \times 10^{-2}$
Gap length d	$= .7$ cm
Normalized drift tube radius γa	$= 1.11$
Normalized gap length γd	$= 1.11$

As in previous tubes, the lens element made from 304 stainless steel will be supported by three radial ceramic insulators. An external lens feed will be used in each system to allow individual adjustment of the lens potentials, when widely different beam perveances are applied. Once the optimum potentials have been determined, the lens diameters for any following tubes can be corrected for operation at cathode potential. The lenses may then be connected internally to the cathode, as was done on previous ESFK's.

1.5 BUNCHER CAVITY

Three buncher cavities will be used in this tube. A cold test buncher cavity has been designed and cold-tested. The cavity, which is of the conventional double reentrant type, is tunable from 2900 to 3150 MHz by means of a capacitive tuner. The measured R_{sh}/Q is 97.5 at midband.

1.6 OUTPUT CAVITY

As the prime purpose of the tube to be built is the study of beam perveance effects and not of broadbanding techniques per se, a simple single gap cavity was chosen as output circuit. Such a cavity has been designed and cold-tested. It is tunable from 3000 to 3070 MHz by means of an inductive tuner, like the one used in the previous L-3668H ESF-klystron. The measured R_{sh}/Q of this cavity is 96.5.

The loaded Q of the output cavity was calculated by using the following equation:

$$Q_L = \frac{1}{2M^2\eta} \cdot \frac{1}{\frac{R_{sh}}{Q_o}} \cdot \frac{V_o}{I_o}$$

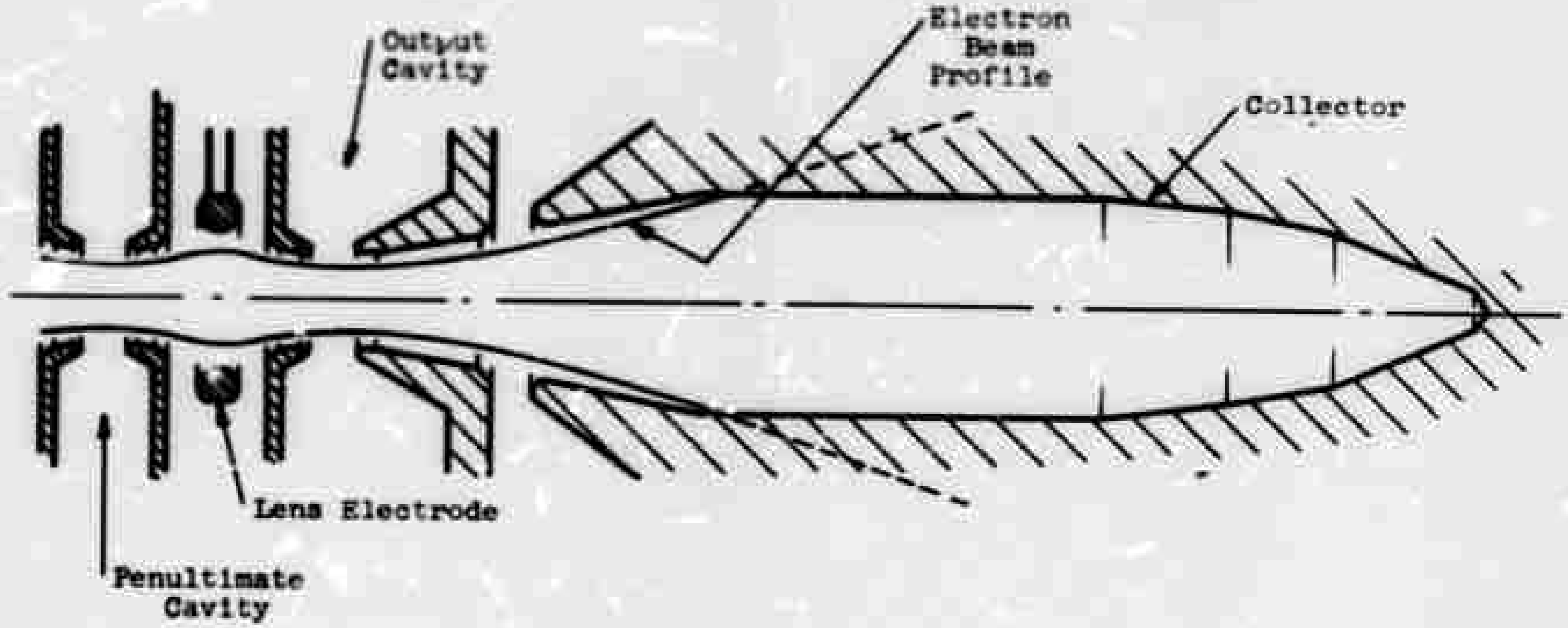
V_o	=	Beam Voltage	=	40,000 V
I_o	=	Beam current (corresponds to beam perveance of 1.5×10^{-6} $A/V^{3/2}$)	=	12 Amp.
M	=	Beam coupling coefficient	=	.9 (assumed)
η	=	Electronic efficiency	=	50% (assumed)
$\frac{R_{sh}}{Q_o}$	=	$\frac{\text{Shunt impedance of unloaded cavity}}{\text{Unloaded Q value}}$	=	96.5(measured)

$$Q_{L_{1.5}} = \frac{40,000}{2 \times .9^2 \times .5 \times 12 \times 96.5} = \underline{42.6}$$

The value compares with Q_L of 45.5 measured on the final cold-test cavity. To be able to match the output coupling by operating the tube at different beam perveance values, an E-H tuner will be located between the klystron output circuit and load circuit.

1.7 RF OUTPUT WINDOW

For this tube, the same output window will be used as in the previous L-3775 1 Mw ESFK. This window will contain a .125" thick beryllia disk 3" in diameter and will be capable of handling 10 kw average power.



BEAM SPREAD CURVE
(COLLECTOR REGION)

Fig. 6

1.8 COLLECTION

The same collector design will be used as in the L-3075 except the entrance nozzle will be changed corresponding to the new beam profile, which can be seen in Fig. 6. This collector is designed for 10 kw average power dissipation.

1.9 VOLTAGE HOLD-OFF PROBLEMS

1.9.1 Gun Region

The chosen ceramic for the gun envelope provides a minimum 3" air gap between the high voltage header flange and ground. The ceramic surface is convoluted to provide an effective path length of approximately 4 1/2 inches. This length should be adequate to hold off the maximum applied voltage of 40 kv.

1.9.2 Modulating Anode Region

The modulating anode is supported like the lenses, by using three radial ceramic insulators with a minimum path length of .450 inch. An external feed-through will be used to allow changing of the voltage, which will be between -9.5 to +16 kv in reference to ground. Since this feed-through is identical to a regular lens feed used in the L-3HKV R (which operated at a voltage of up to 30 kv), no hold-off problems are expected. The voltage gradient between focus electrode of the gun and the modulating anode is in the worst case 350 V/mil when modulating anode is at 36 kV in reference to cathode. Again, this has been proven in previous KIPs's to be an acceptable value.

1.9.3 Lens Region

The lens ring to body voltage is 40 kV. This leads to a maximum voltage gradient of 250 V/mil between lens ring and cavity wall. Due to dielectric of the lens support [illegible] amica, this voltage gradient will be somewhat enhanced. The maximum voltage gradient in the tube will occur between lens lead and the feed through hole. Since the ratio of outer conductor radius and inner conductor radius of the lens feed is 3.0, which is very close to the optimum ratio (2.7) for voltage hold-off, the voltage gradient calculates to be:

$$E_e = \frac{V}{r_e * \ln \frac{r_o}{r_e}}$$

$$E_e = \frac{40,000}{.0785 * \ln 3} = \underline{\underline{464 \text{ V/mil}}} .$$

This voltage gradient is, although somewhat high, still lower than the one used in the L-3975 a 1 Mw ESFK.

2.0 SUMMARY AND CONCLUSIONS

1. A lens system has been designed for a beam with a perveance of $1.5 \times 10^{-6} A/V^{3/2}$ by means of the Litton network analogue and the high speed digital computer. According to trajectory plots, the same system is also suitable for use with a beam of a perveance of $2.1 \times 10^{-6} A/V^{3/2}$. The lens system is consistent with good rf design for the tube.

2. A 1.5×10^{-6} perveance Pierce type gun was designed and the trajectories were checked at different voltages.

3. The buncher cavities have been designed and cold-tested.

4. A single gap output cavity has been designed and cold-tested.

5. The mechanical design of the test tube has been completed, detail drawings have been made and all parts have been ordered.

3.0 PROGRAM FOR NEXT QUARTER

1. A gun assembly will be made and the heater power requirement will be measured in a bell jar.
2. The tube will be assembled and exhausted. The tube should be ready for hot test in the last month of the second quarter.
3. Further theoretical studies of the focusing system for different beam perveance values will be made.
4. Studies of the rf behavior of electrostatically focused beams as a function of beam perveance will be made.

4.0 ADMINISTRATIVE INFORMATION

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

Dr. G. E. Pokorny	69 hours
Dr. A. J. Prommer	41 hours
Mr. H. T. Luchsinger	158 hours
Mr. C. K. Whittaker	89 hours
Mr. A. H. Zanotti	78 hours
Mr. E. K. Shaw	32 hours
Miss P. A. Vartanian	38 hours
Total	505 hours

This report period included a two week vacation shut-down of the facilities.

On May 3, 1966, Mr. Park Richmond, ECOM Project Engineer visited this facility. The overall program plan for the subject contract and details of the technical approach were discussed between him and Messrs. H. Luchsinger, G. Pokorny, and A. Prommer of the Research Department.

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STUDY OF HIGH-POWER ELECTROSTATICALLY FOCUSED KLYSTRONS

First Quarterly Report - 1 May 66 - 31 Jul 66

Luchsinger T. H.; Pohorny G. E. Dr.

November 1966

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DA 28-043 AMC-02253 (E)

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13. ABSTRACT

A periodic electrostatic focusing structure optimized for a beam perveance of 1.5×10^{-6} has been designed utilizing the resistor network analogue in conjunction with a digital computer. The lens electrodes are at cathode potential and are located between each cavity. Also a 1.5×10^{-6} perveance gun was designed with the resistor network. The same gun was checked by applying different modulating anode voltages.

Buncher and output cavity models have been built and cold-tested. The design of the experimental tube has been completed and parts have been ordered.

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