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# HIGH POWER, PERMANENT MAGNET FOCUSED, S-BAND KLYSTRON FOR LINEAR ACCELERATOR USE*

by

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# I. INTRODUCTION

The following discussion outlines the work done and results obtained at Stanford University in the development of a high power S-band klystron tube. The klystron is permanent magnet focused and is designed specifically to provide the rf power necessary for the two-mile linear electron accelerator now under construction at the Stanford Linear Accelerator Center under contract with the U. S. Atomic Energy Commission. The work reported has been done in parallel with industrial development and procurement of klystrons for the Stanford machine.

The accelerator is designed to very strict specifications from the standpoint of energy spread, and must in addition be capable of supplying this well-defined beam over an energy range of from 10 to 20 GeV. The limitations of energy spread correspond in turn to a total phase shift stability of six electrical degrees at each of the 960 feed points to the accelerator.[1] The beam energy specified can be obtained from 240 klystrons, each with power output ranging from six to 24 megawatts approximately and each with its output power divided among four successive feed points. The accelerator also requires that the klystron output must be stable both in amplitude and in phase over a wide range of beam voltages. The accelerator is planned so that the energy could be increased in the future to 40 GeV by installation of a total of 960 klystrons having the same specifications as those presently used.

As a result of the above considerations, the klystron objective specifications were established as follows:

| | | | |
|---|---|---|---|
| Operating frequency | 2856 Mc | Beam voltage | 250 kV max |
| RF pulse width | 2.5 μsec | Microperveance | 2.0 nominal |
| Repetition rate | 60-360 pps | Peak power drive | 240 watts max |
| Peak power output | 24 MW min. | Gain | 50 dB min |

Phase modulation: $1^\circ$ maximum due to heater hum;

$8^\circ$ maximum per % of beam voltage variation;

$1^\circ$ maximum due to any other cause.

Noise: − 40 dB in 1 Mc band up to 5000 Mc;

− 25 dB in 1 Mc band over 5000 Mc.

In addition, it was decided to use permanent magnet focusing because of the great simplification in machine operation introduced by the elimination of the 240 focusing coils, focusing supplies, water interlocks, etc., which would have been required for electromagnetic focusing. Both the tubes which have been built at Stanford and those which are being obtained from industry are designed to the above specifications, with the single exception that tubes will be acceptable if power outputs are somewhat less than that of the objective specifications. A cross section of one of the klystrons built at Stanford, housed in its permanent magnet, is shown in Fig. 1.

This paper will show that although the peak power design objective has not yet been achieved, it is possible to produce in excess of 20 megawatts of power at efficiencies of approximately 35 percent and with gain in excess of 50 dB without introducing any tube instabilities which would be detrimental to operation of the accelerator. The following design points will be considered: (1) electron gun, (2) interaction space, (3) collector, (4) output window, (5) permanent magnet. Discussions of some of the initial experimental difficulties and test results of some of the latest tubes built at Stanford and tested in permanent magnets will then be given.

## II. DESIGN CONSIDERATIONS

### A. Electron Gun

The gun initially used in Stanford's klystron was one designed by J. Picquendar of CFTH.[2,3] This gun was designed as a field-free gun, but took advantage of the fringing field to reduce the diameter of the beam before it entered the anode hole. Although results with this gun design were in general satisfactory, some problems were encountered which made it desirable to design an electron gun specifically for use with the Stanford klystron.

The new gun (Merdinian gun) was designed by following Pierce's theory, with the introduction of an additional correction factor to compensate for the presence of a large anode hole. The design of electrode shapes was carried out in an electrolytic tank, after which the gun was analyzed on an IBM 7090 computer, where Laplace's and Poisson's equations were solved simultaneously. The electro-statically focused minimum beam diameter is approximately 0.9 inch. After the beam passes through the magnetic pole plate, the beam diameter converges to approximately 0.8 inch. It was also found experimentally that this gun operates extremely well under partially confined flow conditions, and that some of the permanent magnets which we have procured exhibit the proper field shape in the gun region for partially confined flow operation; it is believed that the beam diameter is reduced to approximately 0.7 inch by this method.

B. Interaction Space Designs

With the beam diameter given at 0.8 inch, a drift tube diameter of 1-1/8 inches was chosen as a compromise between optimum coupling and low interception. The conventional plasma theory for operation at 250 kV with a microperveance of 2 gives, for these conditions, a reduced plasma frequency of $160 \times 10^6$ cps or a reduced plasma wavelength of 55 inches. The normalized drift tube and beam radii are $\gamma_a = 0.775$ and $\gamma_b = 0.551$. Optimizing gain and efficiency would require a total interaction length of between 20 and 24 inches. However, the condition of permanent magnet operation requires a compromise in length because it is not possible to obtain magnets with substantially uniform and adequately high fields over the desired length.

Computation indicated that by using a total of five cavities spaced apart approximately 3-1/2 inches or 23 degrees (reduced plasma), the small signal gain should exceed 70 dB if all cavities are turned synchronously and 60 dB with the penultimate cavity detuned for optimum efficiency. The total length gap-to-gap under these conditions is 14 inches, and permanent magnets giving an adequate field to focus the beam over a total length of 16 inches have been obtained.

Further design work indicated a potential improvement in efficiency by increasing the drift distances in the output stages of the tube. By slight modifications in the design, it was possible to increase the total interaction space without changing the permanent magnets, and two tubes were built with the modified spacing between cavities. The experimental results are given in Section III.

Because of the small drift distances between cavities, there was the potential problem of coupling at higher order mode frequencies within each cavity. Hence the cavities were made internally with different aspect ratios to avoid oscillations caused by drift tube coupling at frequencies of the second or third resonant mode of the cavity. Subsequent tests showed higher order mode oscillations to be still present in the tube, but it was found that these were caused by a $TM_{12}$ type mode, which can be eliminated by making the cavities asymmetrical (different nose length).

C. Collector Design

The design of a collector for operation with permanent magnet focusing required some special attention because of the high stray magnetic fields existing in the collector region. Because of the focusing caused by these stray fields, it was desirable to reduce the collector diameter below what would normally be called optimum for normal electromagnet operation. In addition, focusing of secondary electrons by this stray field might also have caused unwanted reactions with the main beam in the output section of the klystron.

D. Output Window

The output window consists of a thin $Al_2O_3$ disk brazed in a short section of circular waveguide with abrupt transitions into the rectangular S-band waveguide. Parameters for this window were chosen to give maximum bandwidth and low VSWR. The ghost modes in the S-band frequency range are at 2768 ± 5 Mc and 3620 ± 5 Mc. The VSWR of this window is below 1.1 between these ghost modes and drops to between 1.02 and 1.04 at the operating frequency (2856 Mc).

Because one of the more likely sources of failure of high power klystrons is the window, it was decided to connect the window to the tube by use of all-metal, demountable, copper-to-stainless-steel seals, so that replacement of the window in case of failure could be performed without the necessity of machining on the tube.

One of the main differences between normal klystron output window operation and that for the Stanford accelerator operation is that the output window is exposed to the accelerator vacuum rather than to a pressurized gas.

Three types of window failures have been observed: (1) punctures coupled with internal damage, (2) simple cracking with no other damage present, and (3) local melting of the ceramic material by excessive heat. All three types of failure have been observed on one window which failed on a klystron.

(1) Punctures are thought to occur as a result of initial internal breakdown which takes place within the ceramic (this mechanism was first suggested by Dr. Nergaard of RCA Laboratories, Princeton, New Jersey, while working under subcontract with Stanford University). The internal fault gradually extends to the surface and produces a vacuum leakage path across the window.

Elimination of this type of failure requires operation with the maximum E field applied to the window reduced by a reasonable safety factor from the published values of the dielectric strength of the material. Because the E field may be doubled temporarily by faults in the waveguide and its load, it is essential to operate the system in a very good vacuum, taking all possible precautions to prevent load arcs or at least not permitting them to last more than one pulse.

The wide variation in power levels at which internal breakdown occurs probably stems from a lack of homogeneity in the ceramic materials. We suspect that improvement in fabrication techniques of the ceramics to increase the density will at the same time decrease the range of powers over which ceramics fail internally.

(2) Failure by cracking is associated with heating of the window. The heating is caused not only by the dielectric losses within the material, but also by surface losses associated with multipactor action. Coatings reducing the secondary coefficient of the window have been found effective in reducing the multipactor and the tendency of the window to run hot at power levels of a few magawatts peak.

At the present time, all windows on Stanford tubes are titanium-coated by sputtering in an argon atmosphere, and tests have indicated that some coated alumina windows are capable of passing 150 kW average power without overheating. However, repeated surface arcing will remove the coating and the window will again run hot. The system must therefore be designed to prevent such continuous breakdowns.

(3) The melting observed on the surface can be caused only by a localized arc moving to the surface of the window. This type of failure can probably be eliminated by adequate protective circuitry to turn off the power within a few pulses of the initiation of the arc.

## E. Permanent Magnet

The magnets used to focus the Stanford klystron are barrel shaped and are designed for a gap length of 16-1/2 inches with an inside diameter of approximately 8-1/2 inches, which provides space both for insertion of lead shielding and for easy removal of the tube from the magnet. The maximum outside diameter is approximately 18 inches, and the total weight is nearly 800 pounds.

The typical reversal of the magnetic field on either end of the magnetic barrel was a problem in designing the magnets, because the gun design requires a reasonably accurate field shape in the gun region. Field shaping has been accomplished by using a magnetic shield to reduce the reverse field and incorporating a series of bar magnets in the gun area. These bar magnets are polarized in the same direction as the main field to compensate for the inverse field remaining in spite of the shield. By careful adjustment of the location and number of these bar magnets, the desired field for proper electronic beam forming can be obtained.

One of the main potential problems remaining with permanent magnets is that of cross or transverse magnetic fields. The transverse fields can be reduced by very careful magnetizing, or by magnetic shunts which consist of either thin magnetic plates normal to the main field axis or of thin steel cylinders coaxial to the main field axis. Even so, it is still possible to produce permanent transverse fields in an initially well behaved magnet by local demagnetization on the surface caused by contact of magnetic objects with the side of the magnet. The magnet can usually be restored to proper operating condition by judicious location of small magnetic pieces around the pole plates.

## III. PERFORMANCE TESTS

As a standard test procedure, all klystrons built at Stanford are given an initial test in an electromagnet prior to the final test in one of several permanent magnet structures. This allows complete and thorough analysis and comparison of the klystron behavior under different magnetic focusing conditions during these tests, in addition to monitoring beam voltage, current, and rf output power (both by crystal detector and calorimetrically). Probes were used to monitor the drive power and reflected drive, and to pick up any unwanted radiated signals in the pulse transformer tank.

Tests on tubes using the Picquendar gun in general showed gain substantially as computed, but efficiencies not much higher than 30 percent. In addition, some gun oscillations were detected, particularly after the anode housing had been lengthened to permit better field shaping in permanent magnet operation. However, a return to the shorter anode housing would not fully eliminate the oscillations, although the improved loading between the cathode and anode region and the pulse transformer tank tended to decrease the oscillation amplitude. During many experiments, it was discovered that the voltage range under which oscillations were observed is dependent upon the heater power applied to the cathode, even if the tube is not experiencing temperature limitation. Typical plots of oscillation tendency versus heater power are given in Fig. 2.

Other problems encountered in tubes built originally included the following.

1. If the anode drift tube is not long enough, there is coupling from the input cavity to the anode-cathode housing, which may result in unwanted modulation and variations in performance of the tubes as a function of drive and beam voltage. In our latest design the anode drift distance has been increased to prevent such coupling.

2. As mentioned previously, a $\pi$-mode type oscillation can be excited by the beam in a single cavity; it has been necessary to offset the gap in all cavities to prevent this oscillation from occurring. The frequency of oscillation is close to the second mode ($TM_{12}$ type) of the cavity. Another method to eliminate the oscillation is to introduce lossy pins into the cavity, which decreased the Q in the unwanted mode of operation.

3. Collector oscillations can exist because of the ability of the collector and drift tubes to propagate waves above the cutoff frequency corresponding to their diameter. As a result, there can be regeneration of the cavity oscillation mode described previously. However, it was found possible to change the phase of the reflected waves to the cavity, and thus to eliminate the oscillations, by adjusting collector length.

4. Some high voltage bushing punctures were initially experienced. Careful redesign of the corona ring and of the cathode support posts resulted in a more even field distribution along the length of the ceramic, and the punctures no longer appear to be a serious problem. With the present design the equipotential lines intersect the ceramic at an angle of close to $90^{\circ}$ in the area of highest field stresses.

As explained previously, a gun was designed at Stanford specifically for operation with these tubes, and the performance has been in general extremely satisfactory with the new gun. Approximately 12 tubes have been built using the Stanford gun design, and none have exhibited gun oscillations. The overall performance of the tubes built with this gun indicate that the microperveance is between 1.8 and 2.0. Even with a microperveance of 1.8, the power output from these tubes, focused by either electromagnet or permanent magnet, has exceeded 19 megawatts at 250 kV; when the microperveance approaches 2, power output in excess of 21 megawatts with permanent magnet focusing has been observed at 250 kV with the cavity spacings initially used.

Figure 3 shows typical magnetic field plots under which SLAC 2422 klystrons have been tested. PM-8 was an experimental magnet, and tube performance in this field is not as good as in the field of PM-9. All permanent magnets obtained during the past three months produce fields which are within a few percent of PM-9, and we have been able to duplicate performance from tube to tube and magnet to magnet.

Figures 4 and 5 show the comparison in performance obtained in a given tube under different focusing conditions. Figure 6 compares the performance obtained with two tubes of similar design in different permanent magnets of the PM-9 field. These tubes have drift distances of approximately 3.5 inches between cavities. Except for a slight difference in gain, the performance of the two tubes is identical within the accuracy of the measurements. All tubes built with the Merdinian gun and tested in PM-9 have produced in excess of 19 megawatts at 250 kV.

Two tubes have also been built where the drift distances were increased to approximately 4-3/4 inches and 3-3/4 inches respectively between the 3rd and 4th and 4th and 5th cavities. Unfortunately, complete data in permanent magnet has been obtained for only one of these tubes, and is shown in Fig. 7. The other tube exhibited a small amount of oscillations at voltages in excess of 200 kV. By careful tuning of the permanent magnet, it was possible to eliminate the oscillations, and the power output measured at 250 kV was in excess of 22.5 MW.

The difference between the efficiency of the tubes, Figs. 6 and 7, is startling, particularly in the 200 kV operating region. At present the reasons for the differences are not fully understood.

## IV. CONCLUSIONS

In the process of developing high power klystrons for accelerator use, Stanford has been able to achieve substantial progress and has demonstrated that focusing by permanent magnets is practicable at power levels in excess of 20 MW. The tubes initially built used a Picquendar design gun, and although the operation is in general satisfactory, gun oscillations and tube instabilities were a serious problem. In addition, the degradation of power output obtained in electromagnet and permanent magnet was on the average approximately 8%.

A new gun was designed by Merdinian specifically for this application, and all of the last 9 tubes built using this gun have exhibited power outputs in excess of 19 MW at 250 kV. The average degradation in power output of the tube when operated in electromagnet and permanent magnet is less than 3%. Four tubes have exhibited power outputs in excess of 22 MW, and the efficiency appears to be approaching 40% with the optimum drift distances in the output stages. The stability of these tubes appears to be extremely good. These klystrons are interchangeable in the permanent magnets procured by Stanford. Figure 8 is a photograph of such a klystron assembled to the pulse transformer tank and installed on the support beam as it would be in operation of the accelerator.

Additional work is now in progress to further improve the performance of these klystrons and to achieve over 24 MW of peak power output. The effect of changes in drift distances on efficiency as observed by comparison of Figs. 6 and 7 is rather surprising, and additional work needs to be done to optimize the efficiency at the highest operating voltage levels. In view of the available data, it appears reasonable to predict that a tube can be designed to operate in permanent magnet with a guaranteed output of 24 MW and with the required stability.

## LIST OF REFERENCES


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2. J. E. Picquendar, "Conception et Réalisation de la Cuve Rhéographique a Tracé Automatique des Équipotentielles de la Compagnie Francaise Thomson-Houston," CFTH Report No. 32, (Fevrier 1960); p. 59.
3. R. Metivier, "Les Klystrons Amplificateurs de Grande Puissance de la Compagnie Francaise Thomson-Houston," CFTH Report No. 32, (Fevrier 1960); p. 83.
4. J. Jasberg and J. V. Lebacqz, "High Power Microwave Windows," (presented at Fifth International Conference on Hyperfrequency Tubes, Paris, September 1964).
5. G. Merdinian and J. V. Lebacqz, "High Power, Permanent Magnet Focused, S-Band Klystron for Linear Accelerator Use," (presented at Fifth International Conference on Hyperfrequency Tubes, Paris, September 1964).

# LIST OF FIGURES

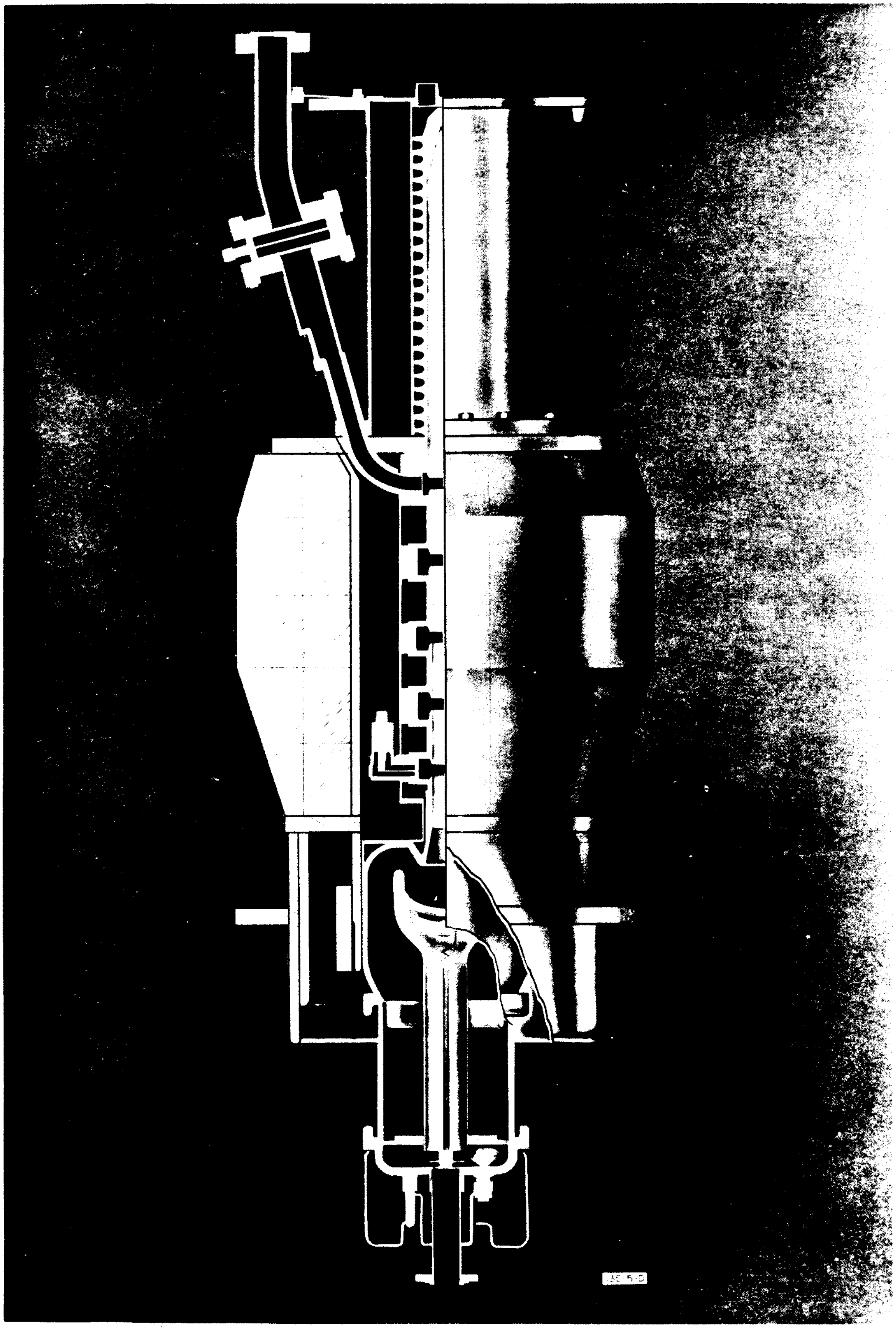


FIGURE I

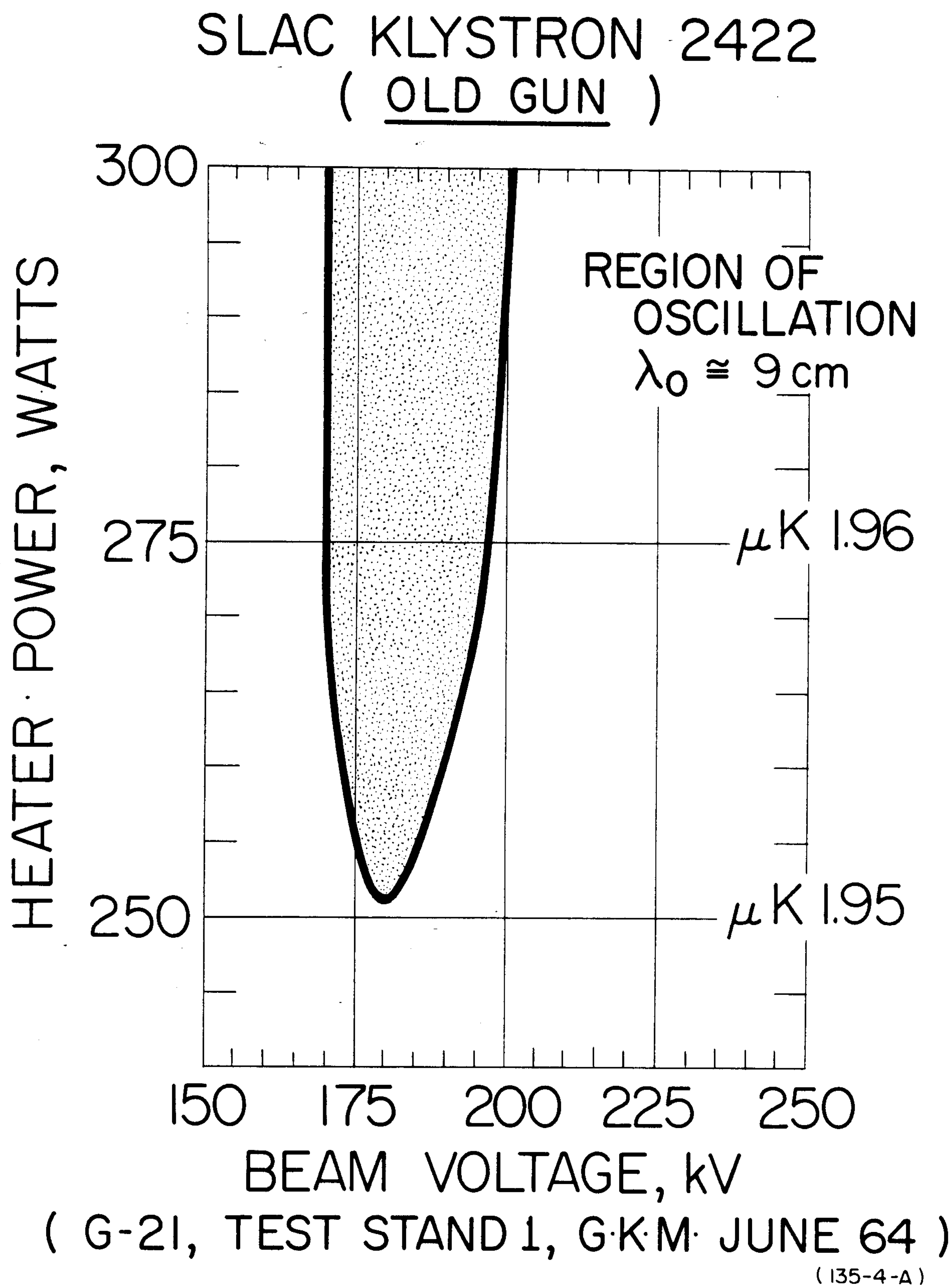
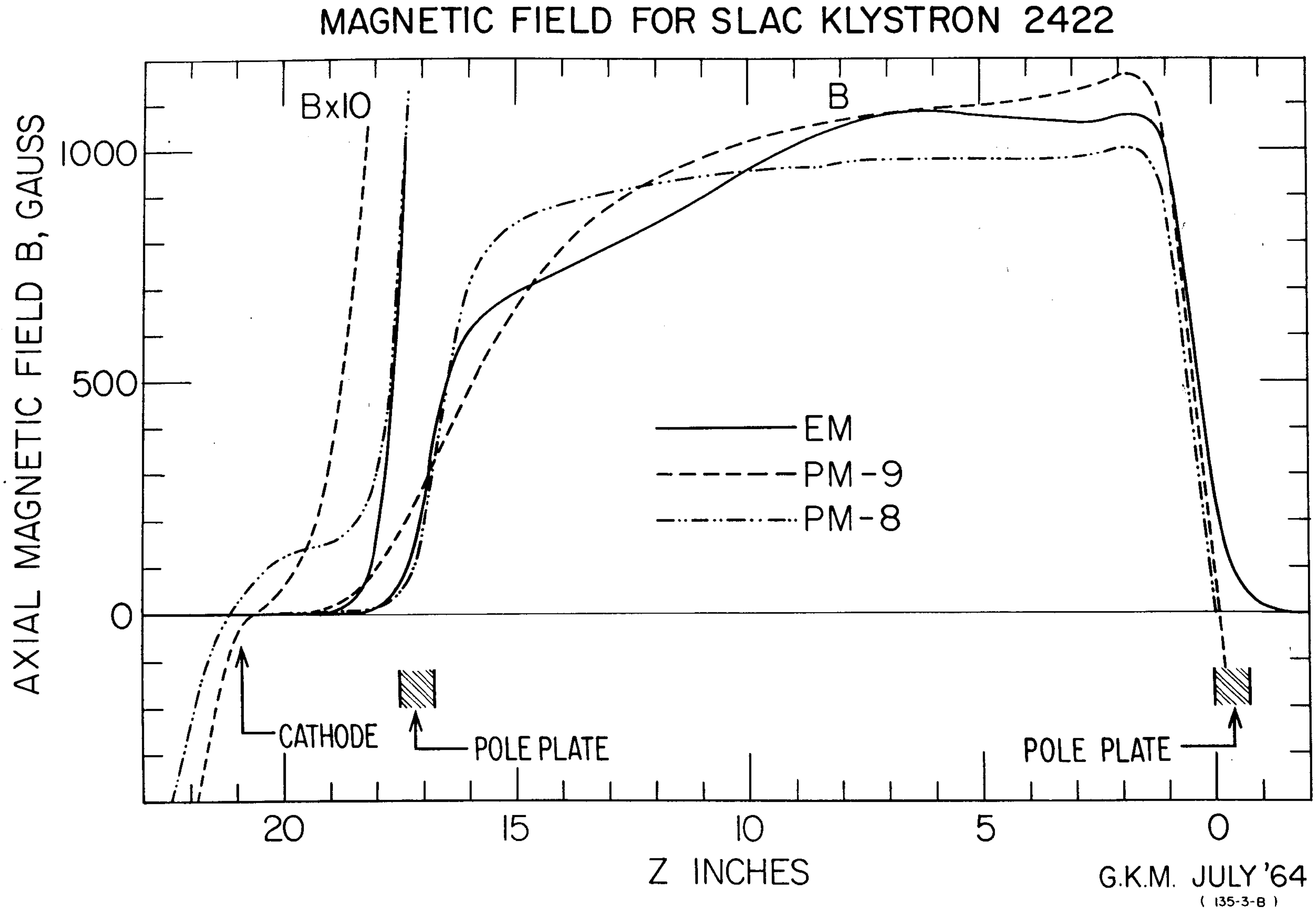

SLAC KLYSTRON 2422
( OLD GUN )
300
275
250
REGION OF
OSCILLATION
$\lambda_0 \cong 9$ cm
$\mu$K 1.96
$\mu$K 1.95
HEATER · POWER, WATTS
150
175
200
225
250
BEAM VOLTAGE, kV
( G-21, TEST STAND 1, G·K·M· JUNE 64 )
( 135-4-A )

FIGURE 2



MAGNETIC FIELD FOR SLAC KLYSTRON 2422
AXIAL MAGNETIC FIELD B, GAUSS
Bx10
B
1000
500
0
EM
PM-9
PM-8
CATHODE
POLE PLATE
POLE PLATE
20
15
10
5
0
Z INCHES
G.K.M. JULY '64
( 135-3-B )


FIGURE 3

TUBE = H-47A DATE AUG-10-64 LOG PAGE 2-10

OPERATOR D. REED TEST STAND = 1

NOTES: ELECTROMAGNET

———— TOP CURVES : FIELD OPTIMUM AT EACH Eb

- - - - - - BOTTOM CURVES : FIELD OPTIMUM AT 250 kV ONLY

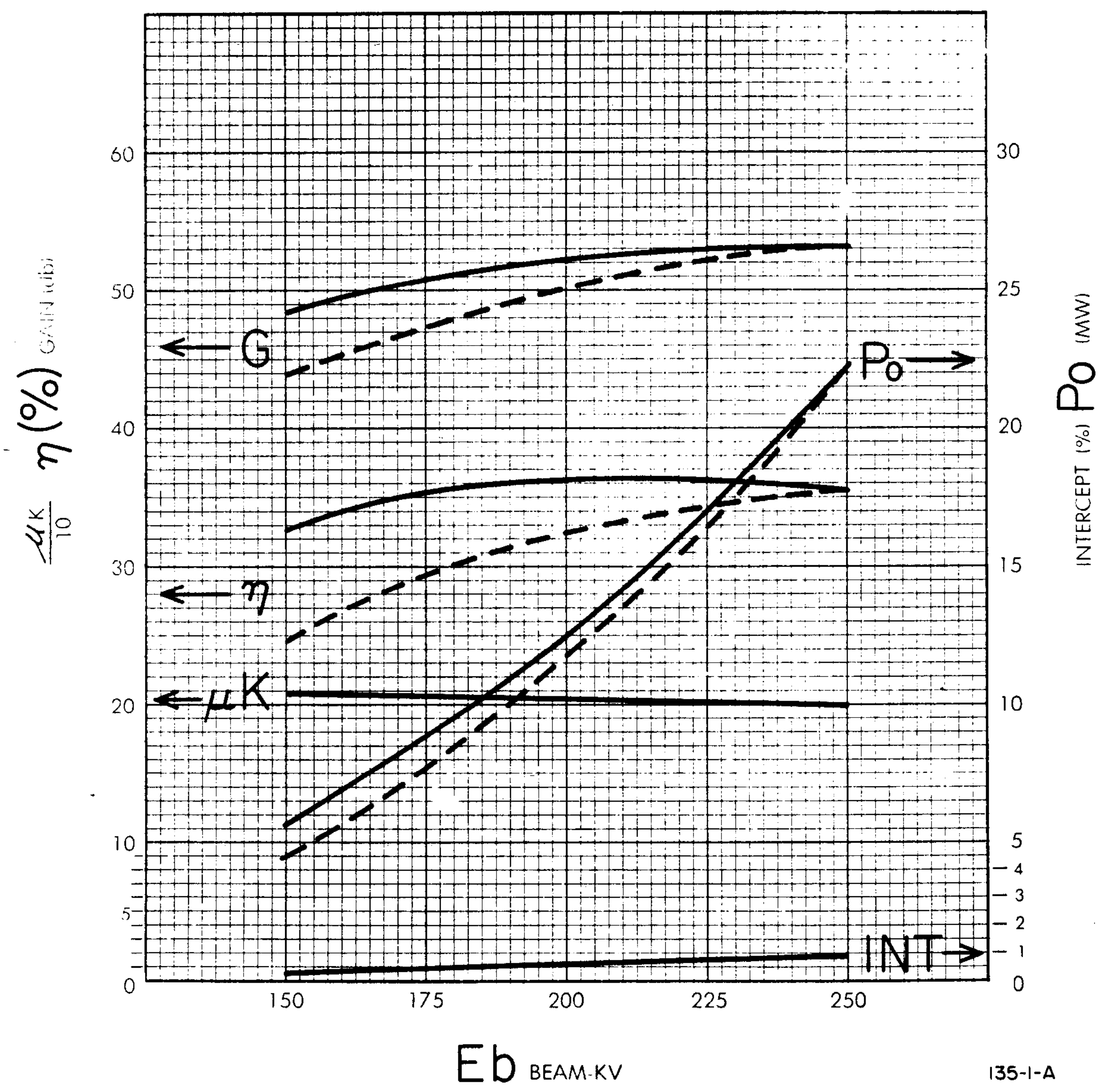



FIGURE 4

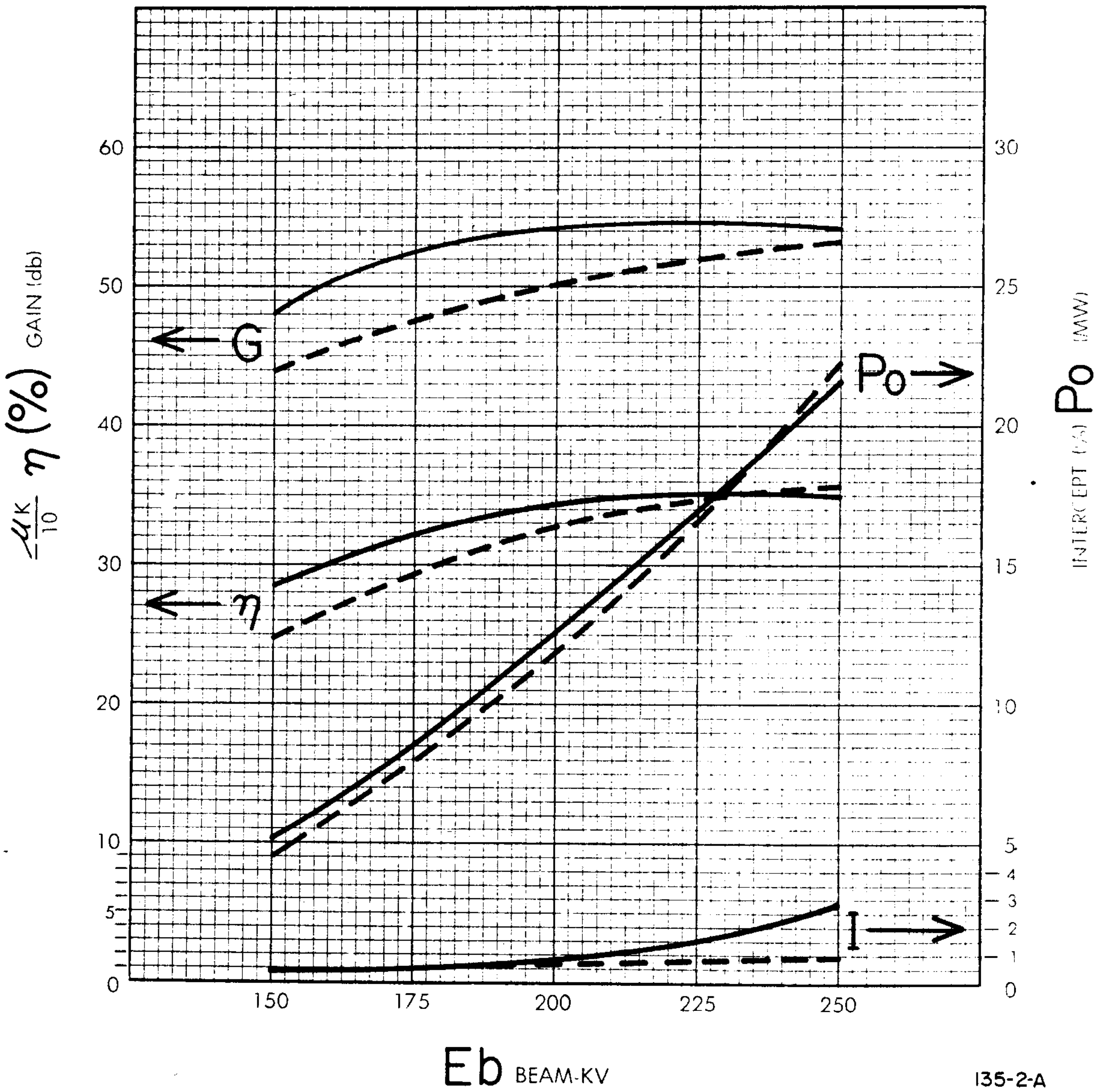
TUBE H-47A DATE AUG-10-64 LOG PAGE 10-13

OPERATOR D. REED TEST STAND = 1

NOTES:

--------- ELECTROMAGNET OPTIMUM FIELD AT 250 kV

——————— PERMANENT MAGNET ( PM-9 )



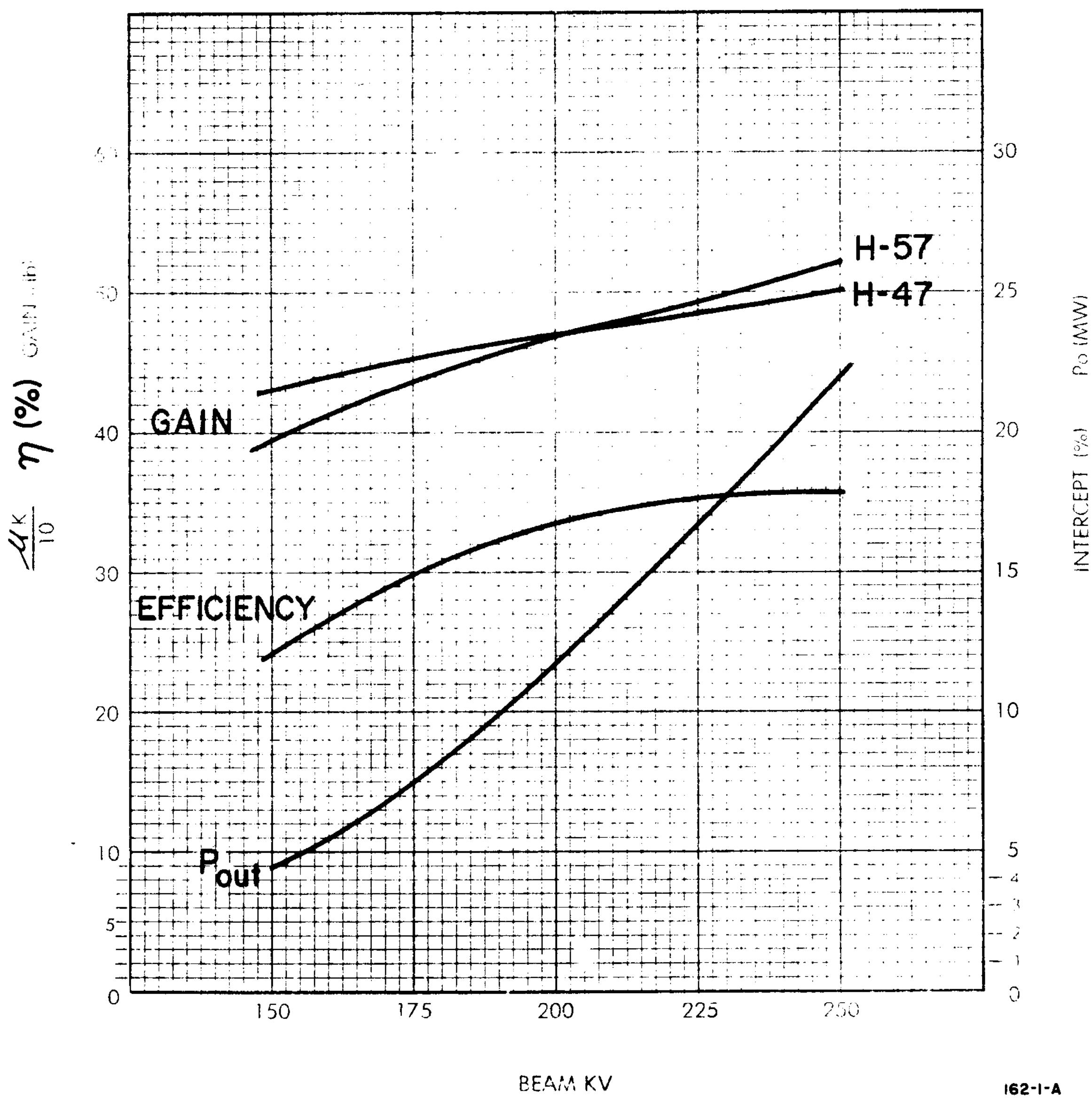

135-2-A

FIGURE 5

TUBE = H-47A and H-57A DATE ______ LOG PAGE ______

OPERATOR ______ TEST STAND = ______

NOTES: PM-9 and PM-13 $\mu K$ between 1.9 and 2




162-I-A

FIGURE 6

TUBE # H 54 in PM # 15 DATE ______ LOG PAGE ______

OPERATOR ______ TEST STAND # ______

NOTES. ______

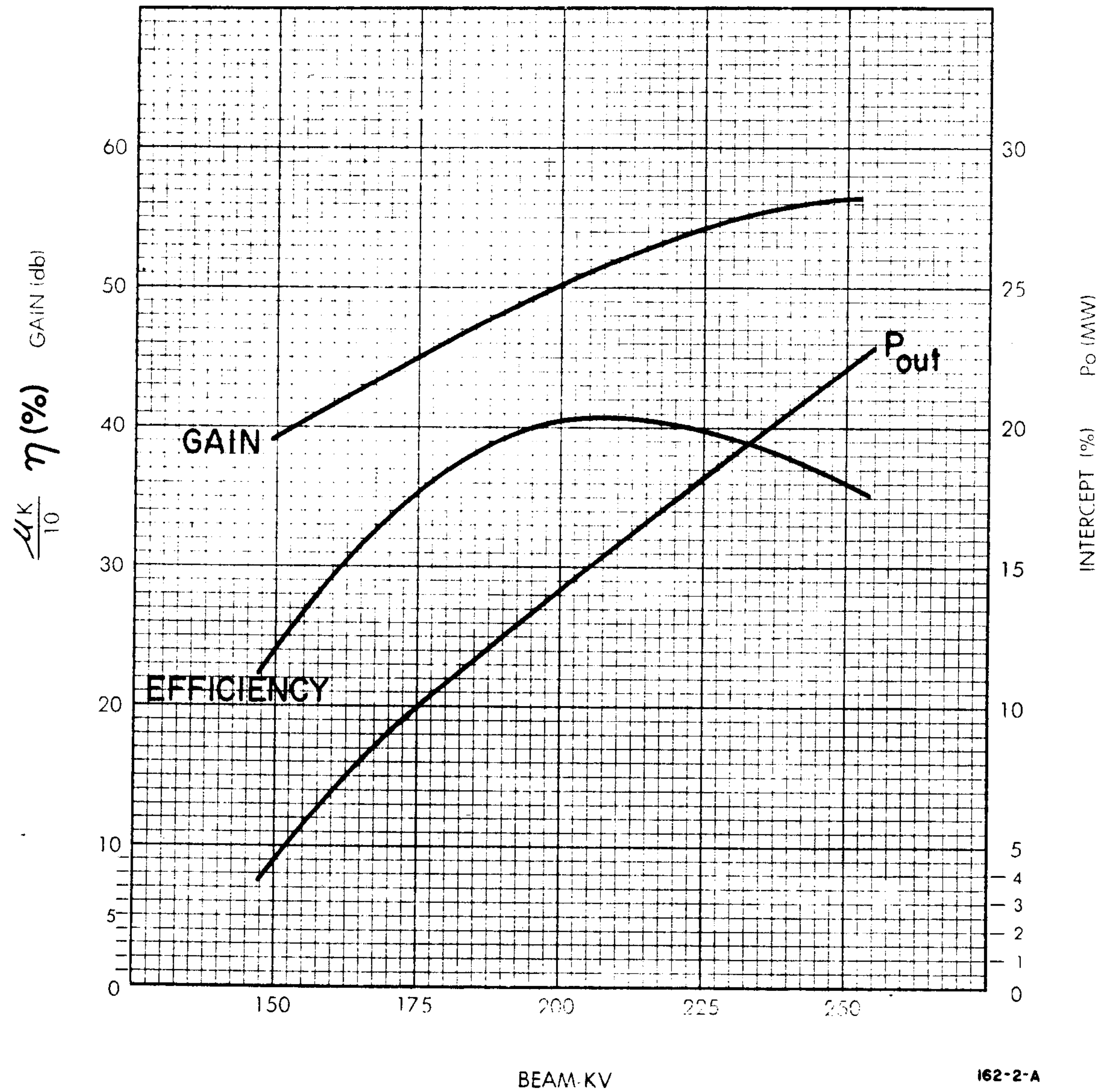



FIGURE 7

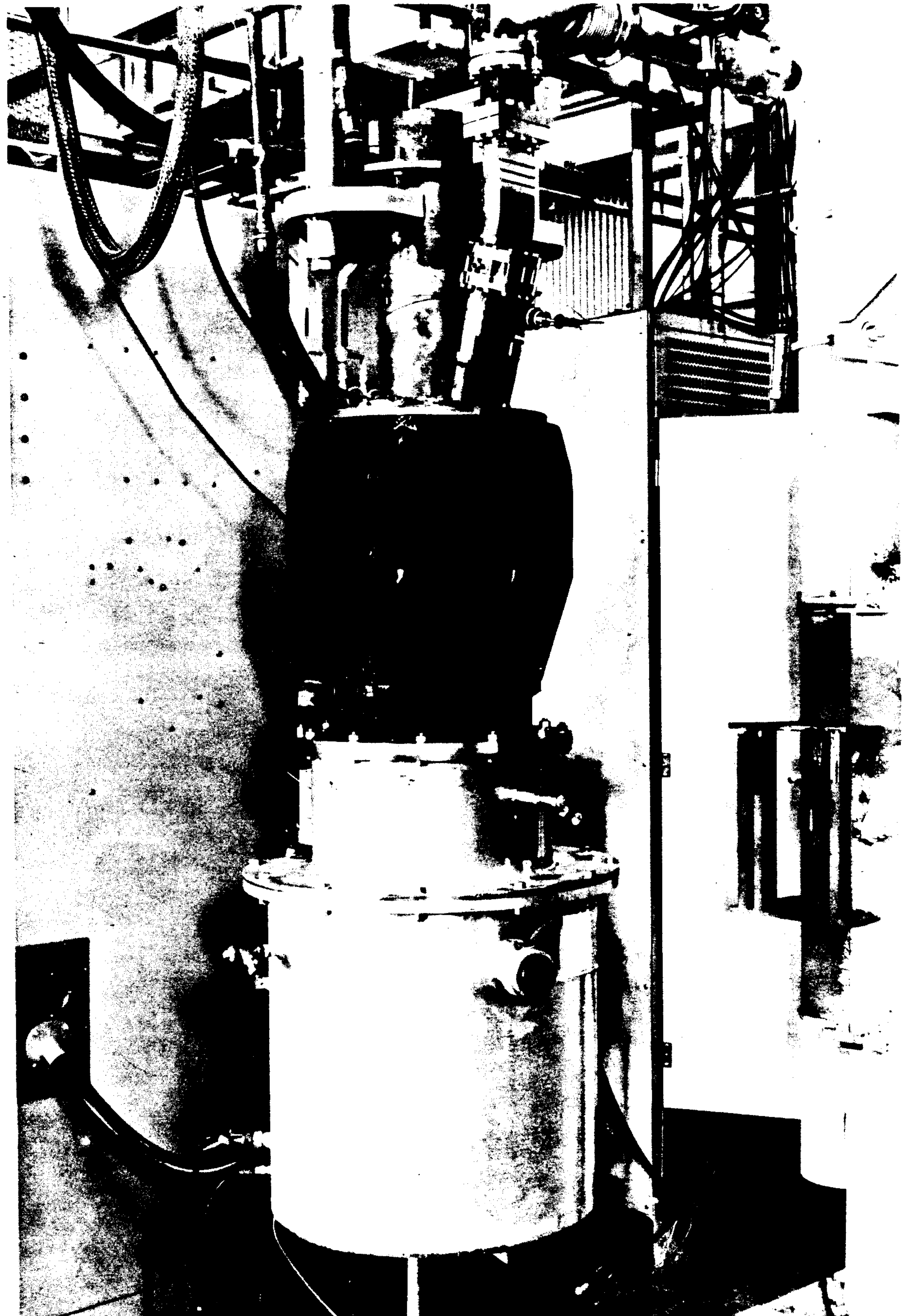


FIGURE 8