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HIGH POWER KLYSTRONS*

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Summary

This paper will review the evolution of high power klystrons and their applications in supplying rf energy for linear accelerators. Other types of possible rf sources were considered for SLAC, and the reasons for the selection of klystrons will be given. A brief review of klystron types in use for various accelerators will also be given, but the emphasis will be on the work done by Stanford and its subcontractors in developing klystrons capable of achieving peak powers in excess of 20 MW and average powers of 20 kW for use with the two-mile Stanford linear accelerator.

Selection of RF Sources

Three main types of rf sources were considered for use at SLAC: the magnetron, the amplitron, and the klystron. Even though Slater and his colleagues were able to demonstrate the use of a large number of magnetron oscillators in an operating machine,[1] the system is complicated and inefficient. The main difficulty arises from the relative instability of heavily loaded oscillators and the problems of accurate phasing between oscillators. In addition, it was felt that the rather short life expectancy and reasonably low peak power of magnetrons would make the tube unsuitable for use in a large accelerator.

The amplitron has the advantages of extremely good efficiency and low phase sensitivity to input voltage. Its main disadvantages result from very low gain and low isolation between input and output, requiring the use of complicated amplifier chains and of many high power isolators. The added cost and complexity and the lowering of the efficiency by the additional amplifier chains requirement made the amplitron solution unattractive for use with the SLAC accelerator.

The klystron amplifier has been used on almost all linear electron accelerators having multiple power sources and operating at microwave frequencies. It appears most suitable for the following reasons: (1) it is a high gain amplifier, which simplifies phasing and driving problems, particularly in a very long machine; (2) the necessary average and peak powers can be easily obtained; (3) the efficiency is reasonable, although not as high as that of other tube types; (4) the high degree of isolation between input and output makes it more stable under conditions of load mismatch; and (5) experience on the Stanford Mark III accelerator over the past ten years and use in many radar applications indicates the potentially long life of this device.

Evolution of High Power Klystrons

The use of high power klystrons for generation of peak powers in the megawatt region in the frequency range of 3000 Mc/sec was initiated at Stanford as a power source for the first multiple source Stanford linear accelerator. In 1944, E. L. Ginzton suggested that it would be possible to build klystron amplifiers each delivering 15 to 30 MW of pulsed power. By 1948, the basic design of a three-cavity high power klystron had been established, and tests confirmed the general validity of the theory and assumptions made. The Mark III accelerator at Stanford still uses klystrons which are basically the same as those designed by the Stanford group over 15 years ago.[2]

In 1951, work was started at Stanford on the further development of high power pulsed klystrons for practical applications.[3] This work resulted in the development of sealed-off tubes capable of approximately 2 MW peak power at S-band (approximately 3000 Mc), 2 MW at L-band (approximately 1300 Mc), and 1 MW at X-band (approximately 9000 Mc). This work was undertaken in conjunction with tube manufacturers, so that the results would be directly applicable by industry in the manufacture of high power pulsed tubes for both radar and linear accelerator applications.

During the 1950's, development work on high power klystrons was carried on at Sperry, Varian, Eimac, Litton, and General Electric in this country; at CSF and CFTH in France; at EMI and AEI in England. The work resulted in the production of tubes capable of 3 MW peak power and 50 kW average power at C-band, 20 MW peak and 54 kW average at L-band, and 10 MW peak and 20 kW average at S-band in this country. The French development work resulted in tubes capable of between 20 and 30 MW peak power at S-band, with average power capabilities in excess of 20 kW.

Use of Klystrons for Linear Accelerators

At the present time klystrons are used as the rf energy source for linear accelerators operated for research, industrial, and medical applications in this country, in Western Europe, in Russia, and in Japan.

The following is a partial listing of klystron types used in accelerator applications. It is not intended to be all-inclusive and any omissions should not be considered as intentional, but rather as reflecting the ignorance of the author of all possible applications.

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Litton Industries has supplied L-band klystrons for accelerators which are in service at Yale University, Rensselaer University, The National Bureau of Standards, and General Atomics, among others. The tubes used are the L-3250, or the more modern version, the L-3944. These tubes are capable of 10 MW peak, 15 kW average, 30dB gain, 6-microsecond rf pulse length, and maximum efficiency approximately 32%. Also in service at General Atomics is another Litton tube, the L-3661, which is capable of delivering 20 MW peak and 30 kW average at 10 microseconds pulse length, with a gain of 45 dB and an efficiency of approximately 37%.

Sperry Electronic Tube Division is also building klystrons for linear accelerator operation. The SAL-321 is in use at the NASA Langley Research Center. The tube is capable of 20 MW peak, 54 kW average at 1300 Mc with a gain of 34 dB and an efficiency of 33% at a pulse length of 30 microseconds. Sperry is also building the SAC-214 which is used in accelerator service at the University of Florida, University of Alabama, and Polytechnic Institute of Brooklyn. This tube is rated at 3 MW peak, 50 kW average, with a frequency range of 5400 to 5900 Mc, operating at a pulse length of 6 microseconds with a gain of 28 dB minimum and an efficiency of 25% minimum.

Thompson-Varian is supplying tubes for accelerators built by Varian Associates. Among these are accelerators in Darmstadt, Germany; Hill Air Force Base; Boeing Radiation Effects Laboratory; and the University of Saskatchewan. These accelerators use the TV-2011 tube with typical power outputs of 20 MW peak and 20 kW average, at pulse lengths of 3 μsec with a gain of 50 dB and an efficiency of 35%. The TV-2014 tubes are used in accelerators at Frascati, Italy and Bonn, Germany. These tubes are rated at 25 MW peak and 30 kW average, 4 μsec pulse length, 50 dB gain, and 40% efficiency. The above tubes are built with a double output system to ease the window problem at high peak and average powers. The TV-2019 tube, which is used on an accelerator in Karlsruhe, Germany, is rated at 10 MW peak, 15 kW average, 5 μsec pulse length, with 50 dB gain and 40% efficiency.

RCA, which has undertaken the development of klystrons specifically for Stanford Linear Accelerator Center use, is also supplying klystrons of the same design for other accelerators such as that at Cornell University.

The first U.S. linear accelerator designed for medical use was powered by a 2 MW S-band klystron built by Stanford, and Stanford also contributed the klystrons used on the medical accelerators at both Michael Reese Hospital, Chicago and the University of Chicago.

CSF has built both the machine and the klystrons which power the accelerator now used at Orsay, France. These klystrons are rated at approximately 25 MW peak, 5 kW average, with a gain of approximately 43 dB and an efficience of 37%.

Klystrons are also used in Japan at the Institute of Nuclear Study, University of Tokyo, as drivers for a linear electron accelerator used as injector for an electron synchrotron. The Russian electron accelerator at Kharkov is also powered by klystrons which are similar in general design and characteristics to those used in the Stanford Mark III accelerator.

Klystrons for Stanford Linear Accelerator Center

The experience acquired in operation of the Stanford Mark III accelerator indicated the desirability of further improvements in the klystron design and performance characteristics. For example, both theory and experiment indicated that for the Stanford two-mile accelerator it would be necessary to have a maximum phase deviation not exceeding 6° from theoretical at any of the 960 feed points of the machine. This phase deviation can be caused by any of the rf components between the main drive source and the feed point of the accelerator, including the main drive line, the preamplifier (booster and sub-booster) klystrons, the waveguide system from the final amplifier to the accelerator, frequency instability in the stable source, and phase variations within the final amplifier tubes. As a result, extremely tight specifications had to be imposed on the phase modulation within the final amplifier. Similarly, amplitude modulation on the rf output pulse would result in spectrum broadening, and the maximum allowable amplitude modulation had to be specified.

Although the simplified theory indicates complete isolation between the amplifier stages in a klystron, in practice some oscillation or feedback mechanisms are possible, either due to reflected electrons or to a tendency for cavities to oscillate at higher than the driving frequency. In addition, in many klystrons operating at this power level, oscillations in the gun structure have been observed which can cause phase and amplitude instability in the output.

The number of klystrons involved in the SLAC operation necessitated some deviations from the normal practice. For example, a careful study of the focusing problems indicated that there was a potential saving in eliminating the electromagnets and their power supplies and water cooling requirements. Hence, it was decided to design the tube in such a way that it could be focused by permanent magnets. Following the Stanford Mark III practice, it was deemed desirable to evacuate the waveguide runs between the klystron and the accelerator.

Another deviation concerns the method of mounting the tube. Because of the length of the accelerator and the necessity of accurate alignment, it is expected that the feed points may move with respect to the building by several inches. To maintain phase stability in the waveguides, the whole waveguide system must be moved with the accelerator; hence, it was necessary to attach the klystron to a movable frame. The solution has been to hang up the klystron and pulse transformer tank to minimize the tolerance problems in making the waveguide-to-klystron vacuum joint. This system has the additional advantage of allowing variations in overall klystron length without having to change the mechanical installation system. Hence, flexibility is left for future improvements in the klystron design.

The following table gives the objective specifications of the klystrons for SLAC, and a comparison of these specifications with those of the klystrons used at Stanford on the Mark III accelerator.

COMPARISON OF MARK III AND SLAC KLYSTRON SPECIFICATIONS

		MARK III KLYSTRON	SLAC KLYSTRON (Objective Specs)
Operating Frequency	Mc/sec	2856	2856
RF Pulse Width	µsec	2	2.5
Repetition Rate	pps	60	60-360
Peak Power Output	MW	20	24 *
Heater Power	watts	600	270
Beam Voltage	kV	325	250
Beam Current	amperes	185	250
Microperveance		1	2
Peak Drive Power	kW	10	.24
Gain	dB	33	50
Amplitude Modulation	%		1
Phase Modulation	degrees		1 (heater hum) 8 (per % beam voltage variation) 1 (any other cause)
Noise			- 40 dB in 1 Mc band up to 5000 Mc - 25 dB in 1 Mc band over 5000 Mc
Focusing		Electro-magnet	Permanent magnet

* Acceptance specs: 21 MW at 250 kV, 12 MW at 200 kV

Design Considerations and Development Work

The following summary of the design considerations and development work done on the klystrons for SLAC will be primarily concerned with the Stanford development; parallel work has been done in industry and the main differences between the various approaches and results will be pointed out.

Research and development subcontracts had initially been negotiated with RCA and Sperry, with the main purpose of establishing the feasibility of permanent magnet focusing and of demonstrating a tube design which could be manufactured in quantities. Production contracts for the delivery of 72 tubes and permanent magnets, with add-on option features, were signed later with these companies. In addition, contracts for the delivery of 6 tubes and magnets have also been signed with Eimac and Litton.

In the following review, the various components of the klystron will be considered separately.

Electron Gun

Stanford's klystron initially used a gun designed by J. Picquendar of CFTH.[4,5] This gun, designed as a field-free gun, took advantage of the fringing magnetic field to reduce the beam diameter at the entrance to the anode. Although the results observed at Stanford with this gun were in general satisfactory, some gun oscillation problems were encountered after a modification of the physical length of the anode enclosure. As a result, G. Merdinian of Stanford designed a gun specifically for use with the Stanford klystron.

This 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 electrostatically 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.

With this gun, gun oscillations have been virtually non-existent, and it turned out that the entrance conditions in the magnetic field were not as critical as expected. The result was a generally more satisfactory operation of the tubes in permanent magnets than had been observed with the Picquendar gun.

Like Stanford, RCA started their development program by using Picquendar's gun. Unlike Stanford, RCA has found practically no oscillation problems with the gun, and has gradually been able to improve the entrance conditions to the point where the tube performance using their gun is very similar to that of the Stanford tube using the Merdinian gun.

Sperry is using one of their own guns, which is designed to operate in a field-free region and to achieve Brillouin focusing for the beam. Originally, many oscillations were observed with this gun, but the problem was cured by the use of judiciously placed one-half wave-long slots in the focus electrodes.

Eimac initially was planning to use a gun which they had designed specifically for operation under partially confined flow conditions. The advantage of a confined flow gun is the potential improvement in efficiency. Unfortunately, heavy oscillations were observed with this gun, and lack of time to determine the cause and cure of the oscillations forced Eimac to use the Merdinian gun.

Litton is using the Merdinian gun. The first tube they built showed heavy gun oscillations. The cause of these oscillations was traced to a change in the geometry of the gun support structure. The structure has since been modified to duplicate that used at Stanford, and no further oscillation problems have appeared.

Interaction Space

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 160×10^6 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.

Computations indicated that by using a total of five cavities fixed tuned, spaced apart approximately 3-1/2 inches or 23 degrees (reduced plasma), the small signal gain should exceed 70 dB if all cavities are tuned 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 $16\frac{1}{2}$ inches have been obtained.

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 designed 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).

Another method to eliminate cavity oscillations is to introduce losses in the cavity, either by plating the whole cavity with lossy material (Litton technique) or by introducing frequency selective losses, such as pins or loops, into the cavity (RCA technique).

In addition, it has been found that if the anode drift tube is not long enough, there may be 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.

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 tubes were built with the modified spacing between cavities. The results are given below.

The drift distances used by Sperry were initially the same as those used by Stanford (standard tube), and there appeared to be difficulties in achieving full power specifications. Work done by Sperry in modifying the drift distances indicates an improvement in performance similar to that seen at Stanford. The improvement in performance through drift distance modification has not been as spectacular in the case of RCA tubes, but their drift distances were initially closer to the optimum.

Additional work in further improvement of efficiency is being contemplated. The use of hybrid tubes, where the high gain stages are designed as klystron, and the output stages have circuits approximating those of traveling-wave tubes, indicates the possibility of higher efficiency.

Specific attention in the use of such structures must be given to the possibility of oscillations in the output circuit, which would easily produce phase variations in excess of our specifications.

Collector Design

The design of a collector for operation with permanent magnet focusing required some special attention due to 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.

Collector oscillations can exist because of the ability of the collector and drift tubes to propagate waves above the cut-off 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.

Although Stanford has never observed oscillations which were demonstrably caused by the collector, both Sperry and RCA have been troubled by unwanted collector phenomena. These may appear as regeneration at the drive frequency, resulting in an output pulse length independent of the drive pulse length, or in spurious outputs at frequencies other than the drive frequency.

Output Window

The output window used by Stanford 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.[6] 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 after the initiation of the arc.

RCA is using a thin alumina disk window, but instead of brazing techniques they are using a compressed seal technique, which has proven to be very satisfactory in making vacuum seals. They have experienced some heating problems which resulted in cracking windows, and which also have been resolved by evaporating titanium on the window surface.

Sperry has been using an alumina window, approximately one-half wave-thick with what appears to be good success. Litton is using alumina windows, titanium coated to prevent excessive heating and eventual cracking. Eimac uses alumina thin disk windows in the pillbox configuration, and are coating the windows to prevent excessive heating. To date the windows have performed satisfactorily.

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 generally 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 either of 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. In addition, Stanford has built a magnetizer to bring magnets back to full specifications if they are accidentally weakened beyond the useful range of magnetic fields.

RCA is procuring magnets to specifications which carefully limit the maximum amplitude of transverse fields, as well as the range of acceptable magnetic fields. Sperry uses magnets which match the requirements for a Brillouin focused beam.

Satisfactory magnets have been obtained from Arnold Engineering Co., Crucible Steel Co., General Electric Co., and General Magnetic Corp.

Klystron Performance

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 are used to monitor any unwanted radiated signals in the pulse transformer tank, and the forward and reflected drive power are monitored by directional couplers.

Essentially three types of tubes have been built and tested at Stanford during the development work on this problem.[7] The first type uses the Picquendar gun and a standard body (approximately equal spacing between cavities). The second type uses the Merdinian gun and the standard body. The third one uses the Merdinian gun and the XM-3 body, in which the drift distances in the output section have been increased. Figures 1, 2, and 3 give the average performances measured for the three types of tubes when operated in electromagnet. The improvement in performance at high voltages is particularly borne out by Fig. 4, which shows a direct comparison of the latest and the earliest Stanford design.

Having achieved satisfactory performance with tubes in electromagnets, a comparison of the operation of tubes in permanent magnet is now of interest. Figure 5 shows plots of the electromagnetic field which, in general, was found to be optimum for Stanford-designed tubes, and a plot of typical permanent magnet fields which have been achieved. 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 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 6 and 7 show the comparison in performance obtained in a given tube under different focusing conditions, and Fig. 8 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 fields have produced in excess of 19 MW at 250 kV.

The first tube built in which the drift distances were increased to approximately 4-3/4 inches and 3-3/4 inches between the 3rd and 4th and 4th and 5th cavities (XM-3 body) demonstrated the performance shown in Fig. 9. All other tubes of the same design have given substantially the same power output. Only one tube exhibited output power of less than 21 MW in permanent magnet at 250 kV, and it is suspected that the field of that particular magnet had been degraded at the time the tube was tested. In general, the performance in permanent magnet is somewhat lower than that obtained in electromagnet with optimum focusing; however, the degradation is very small, of the order of 3% at 200 and 250 kV.

Although the Stanford tubes do not show any evidence of oscillations, there is occasional amplitude and/or phase modulation which appears to result from heater hum. The heater package was redesigned in an attempt to eliminate the trouble completely; although a very great improvement has been observed, there are still occasional tubes where heater hum modulation is just outside of the acceptable limits.

As of now, the results obtained by RCA have closely duplicated those of Stanford. RCA has gradually introduced improvements in their tube design and fabrication, and are now able to deliver tubes which meet all acceptance test specifications. They also have had to pay very close attention to small details which can cause unwanted jitter, making the tubes unacceptable.

Sperry has spent considerable time and effort to bring their tubes to full specifications, and again attention to detail was necessary to eliminate both gun and body oscillations, and to allow the achievement of required power output. An improvement in power output similar to that exhibited in Fig. 4, although not quite as pronounced, was achieved by Sperry by changing the drift distances in a manner similar to the Stanford changes. As a result, Sperry has now delivered tubes meeting acceptance test specifications.

Litton and Eimac have both been able to deliver tubes which meet the acceptance test specifications; these tubes are very close cousins of those built by Stanford, except for obvious differences in techniques in the fabrication area.

Conclusions

In the process of developing high power klystrons for accelerator use, Stanford has been able to achieve substantial progress and to demonstrate that focusing by permanent magnets is practicable at power levels in excess of 20 MW. Figure 10 is a photograph of a cutaway of the tubes built initially by Stanford for use on the Mark III accelerator. By comparison, Fig. 11 shows a cutaway view of the Stanford design tube which can be used on the two-mile accelerator of the Stanford Linear Accelerator Center, and Fig. 12 is a photograph of a Stanford klystron installed ready for use in a mock-up section of the linear accelerator.

The tubes using the Merdinian gun design have been free of gun oscillations, have shown power outputs in excess of 21 MW at 250 kV, and efficiencies approaching 40% at 200 kV, in permanent magnets. Klystrons and magnets are interchangeable. Similar results have been achieved by industrial firms who have worked on our problems.

With additional work to further improve the performance, it appears reasonable to predict that tubes can be designed to operate in permanent magnets at efficiences of approximately 40%, which would correspond to power output of 85 MW at 250 kV.

One of the main concerns in operating an accelerator of the size of the SLAC machine is the cost or maintenance of tubes. Hence, all tubes have been designed so they can be repaired at a fraction of the cost of a new tube. Also of prime importance is the development of a long-lived tube. Only experience can tell when such long life has been achieved. Preliminary indications from life tests give a promise that the life will initially exceed 1000 hours, and experience with the Mark III accelerator at Stanford indicates that it should then be possible to predict a life exceeding 3000 hours after a few years of operation. Experience with klystrons used in the radar field also indicates that such predictions are realistic.

References

1. P. T. Demos, A. F. Kip, and J. C. Slater, "The MIT Linear Electron Accelerator," J. Appl. Phys. 23, 53 (1952)

2. M. Chodorow, E. L. Ginzton, I. R. Neilsen, and S. Sonkin, "Design and Performance of a High-Power Pulsed Klystron," Proceedings of the IRE, 41, No. 11, (November 1953).

3. M. Chodorow, E. L. Ginzton, J. Jasberg, J. V. Lebacqz, and H. J. Shaw, "Development of High-Power Pulsed Klystrons for Practical Applications," Proceedings of the IRE, 47, No. 1 (January 1959).

4. J. E. Picquendar, "Conception et Realization de la Cuve Rheographique a Trace Automatique des Equipotentielles de la Compagnie Francaise Thomson-Houston," Rev. Tech CFTH No. 32 (February 1960).

5. R. Metivier, "Les Klystrons Amplificateurs de Grande Puissance de la Compagnie Francaise Thomson-Houston," Rev. Tech CFTH No. 32 (February 1960).

6. J. Jasberg and J. V. Lebacqz, "High Power Microwave Windows," Proc. Fifth International Conference on Hyperfrequency Tubes, Paris, September 1964.

7. G. Merdinian and J. V. Lebacqz, "High Power, Permanent Magnet Focused, S-Band Klystron for Linear Accelerator Use," Proc. Fifth International Conference on Hyperfrequency Tubes, Paris, Sept., '64.

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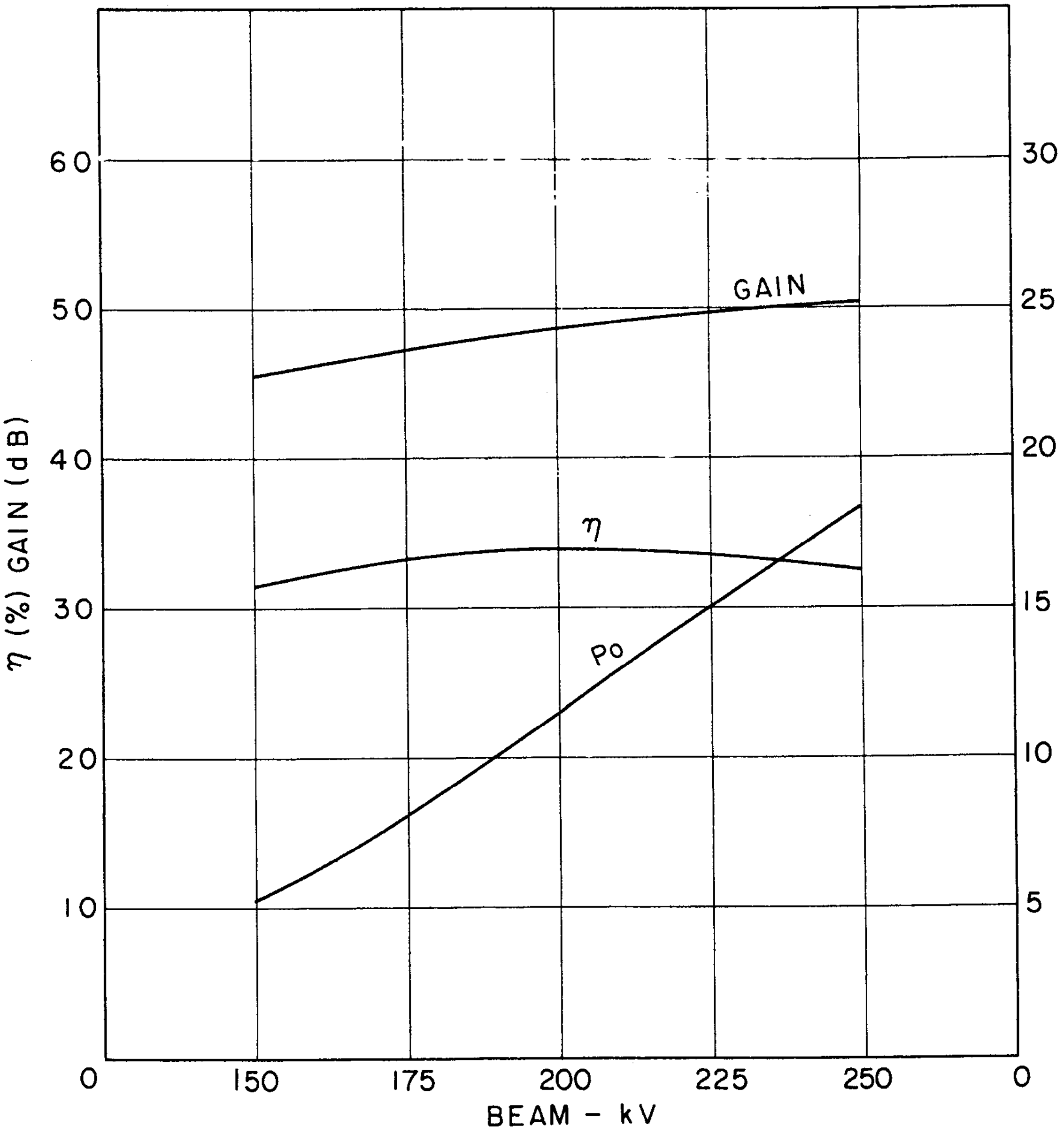


FIG. 1

234-1-A

Stanford 2422 klystron, standard body, Picquendar gun, electromagnet focusing. Average performance for tubes tested between September 27 and December 31, 1963.

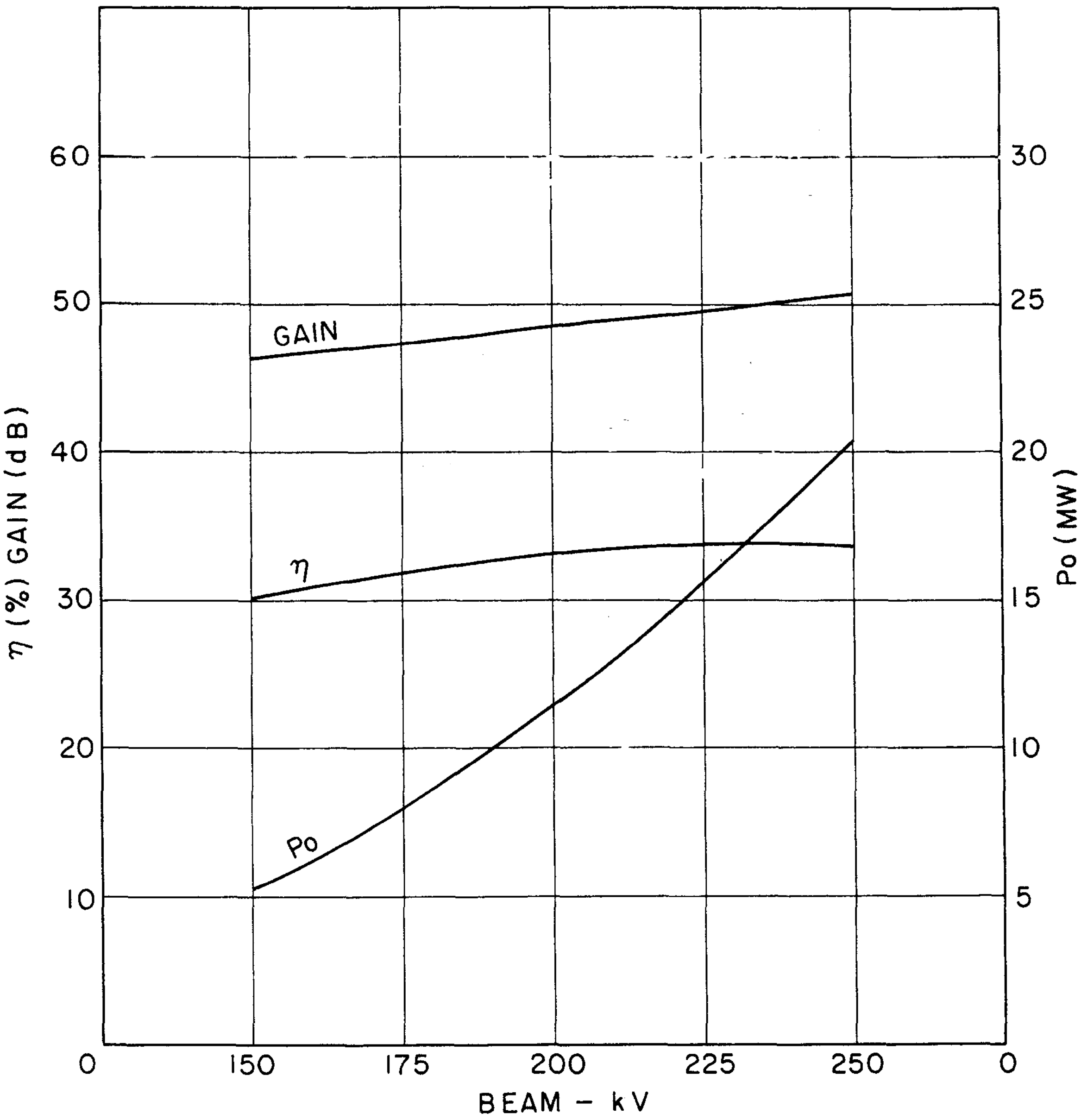


FIG. 2

Stanford 2422 klystron, standard body, Merdinian gun, electromagnet focusing. Average performance for tubes tested between October 1, 1964 and January 1, 1965.

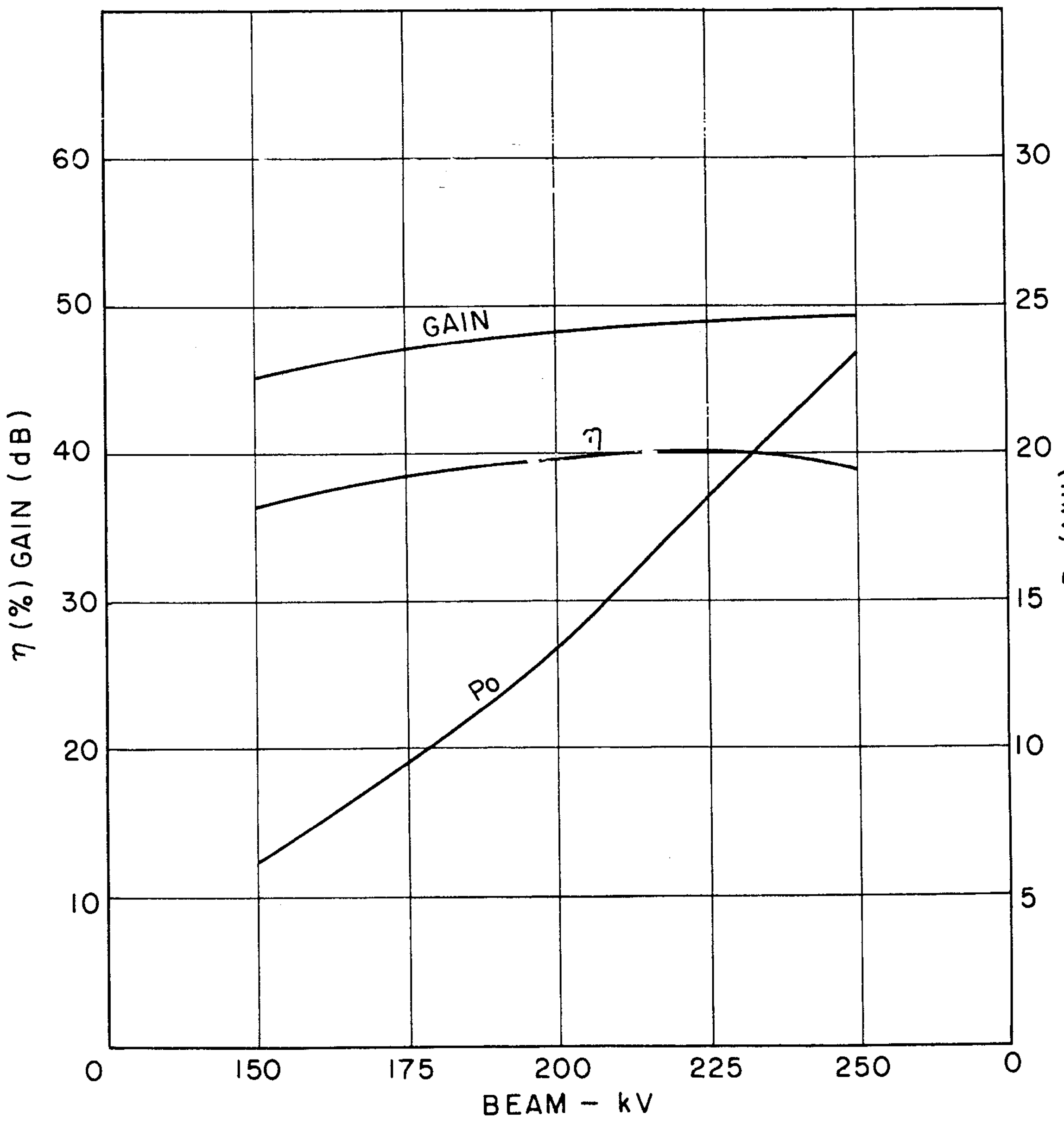


FIG. 3

234-3-A

Stanford 2422 klystron, XM3 Body, Merdinian gun, electromagnet focusing. Average performance for tubes tested between October 1, 1964 and January 1, 1965.

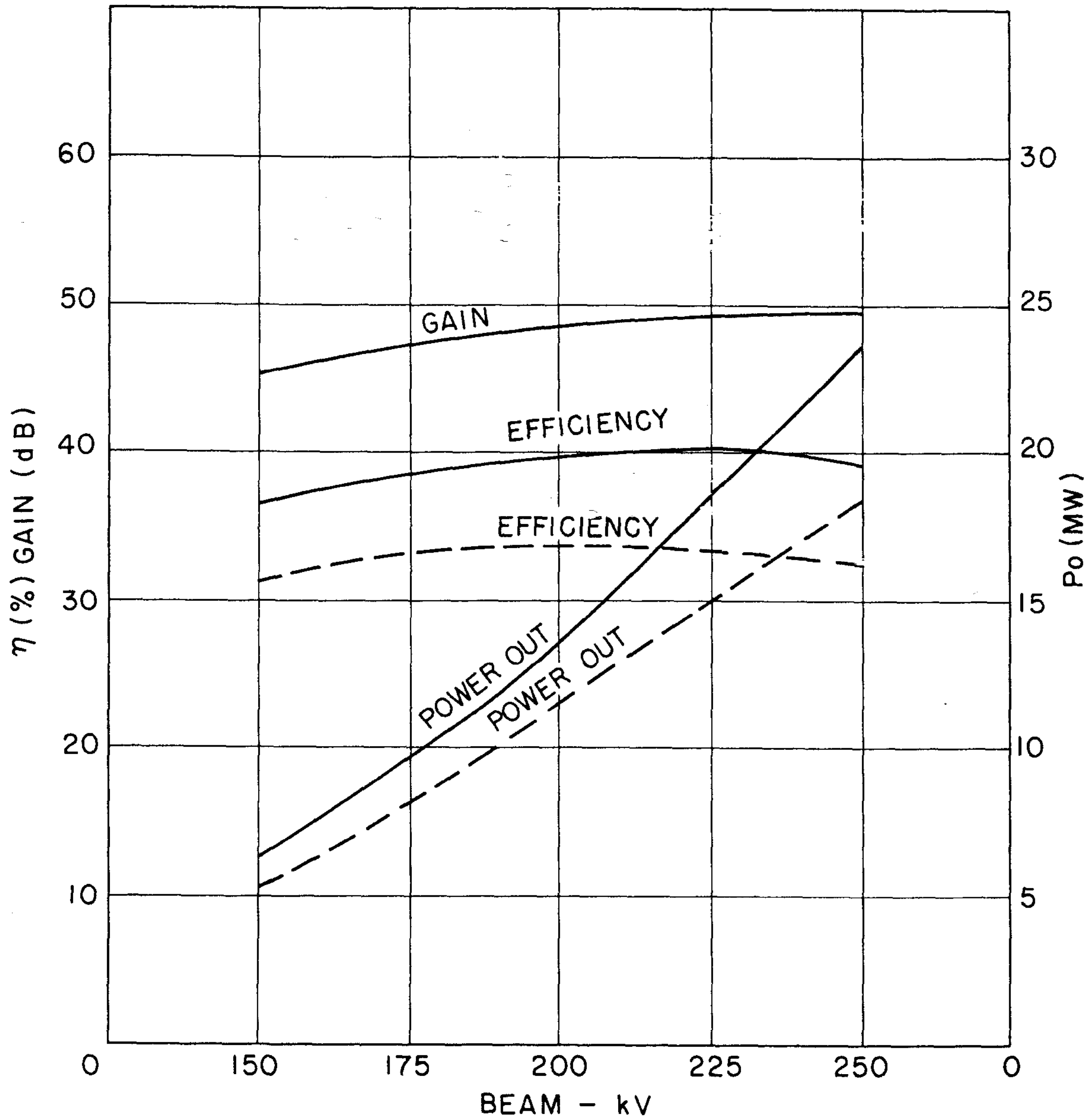


FIG. 4

234-4-A

Comparison of klystron performance (electromagnet focusing).

——— Stanford 2422 klystron, XM3 Body, Merdinian gun, tested between October 1, 1964 and January 1, 1965. Average of 10 tubes.

– – – Stanford 2422 klystron tested between September 27 and December 31, 1963. Average 9 tubes.

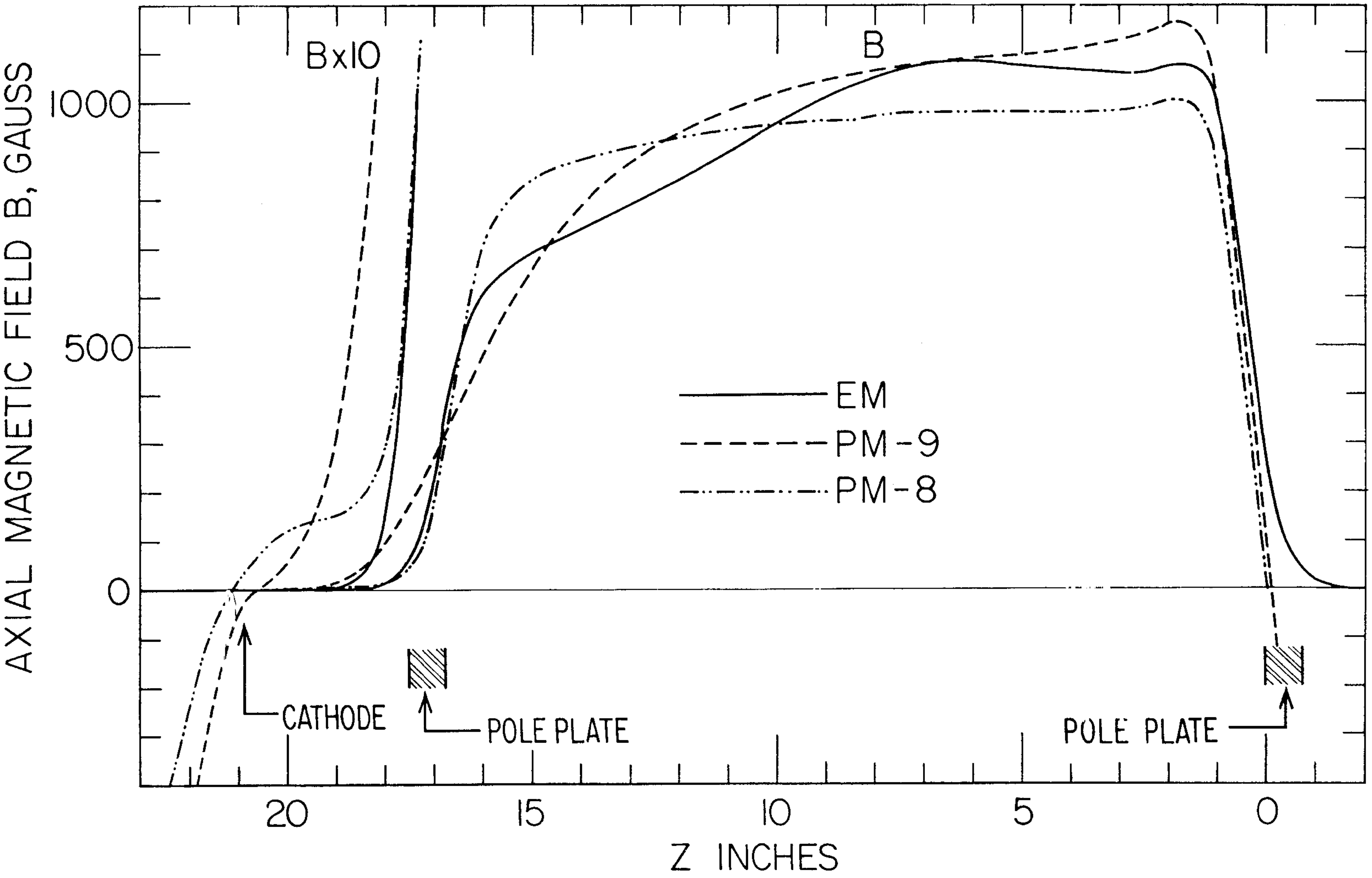


FIGURE 5

MAGNETIC FIELD FOR SLAC KLYSTRON 2422

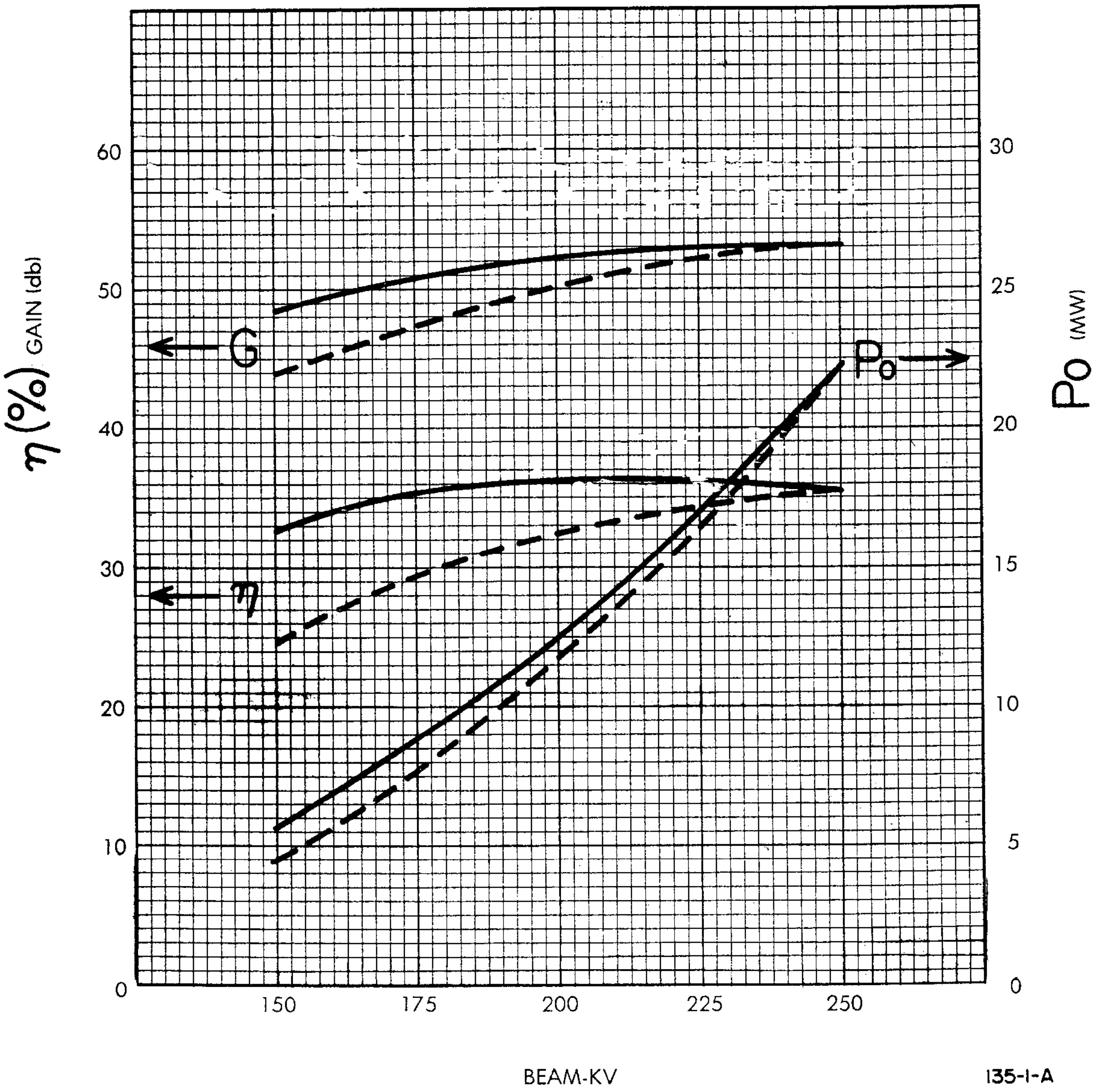


FIGURE 6

Stanford 2422 klystron, standard body, Merdinian gun, electromagnet focusing.

——— Top curves: Field optimum at each Eb.

— — — Bottom curves: Field optimum at 250 kV only.

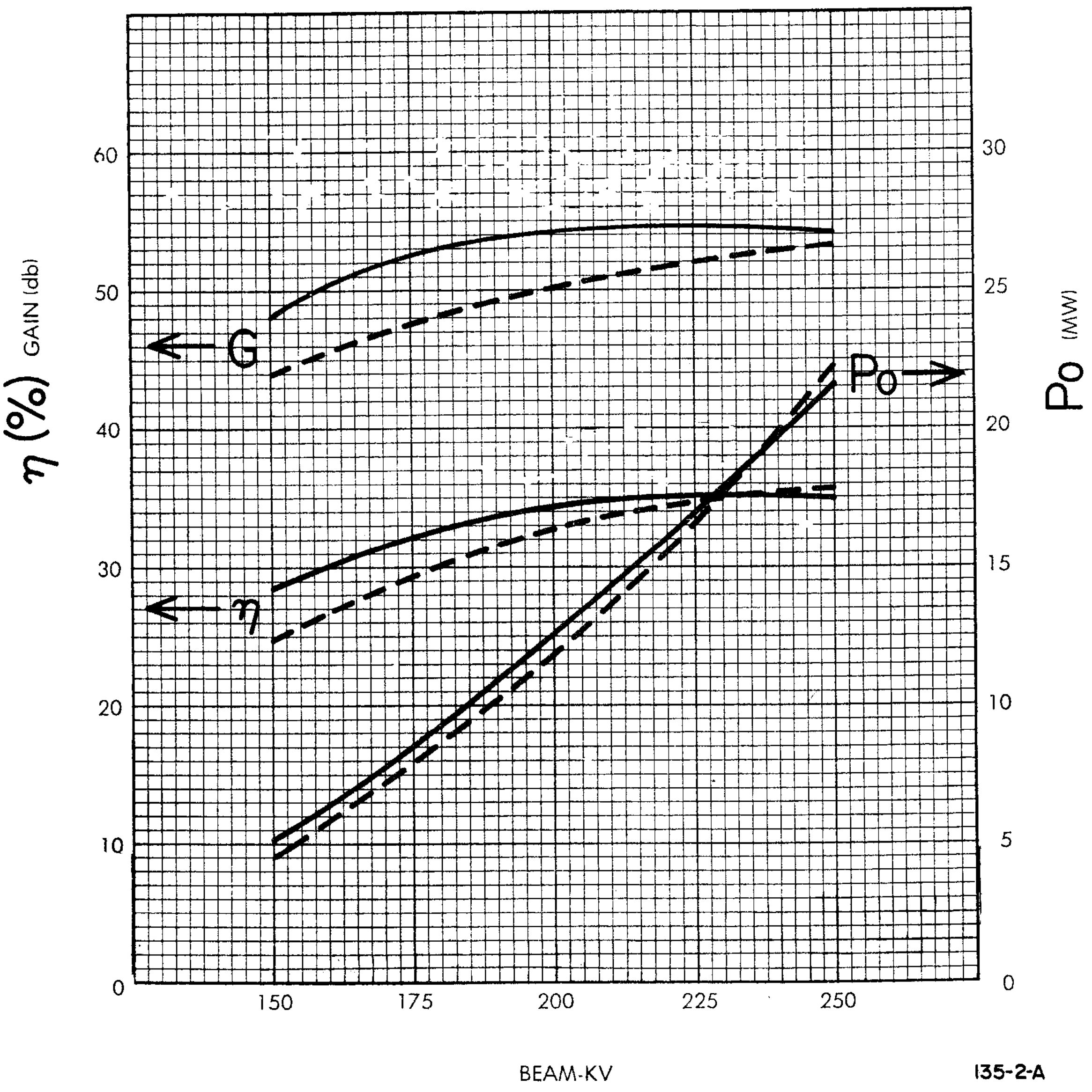


FIGURE 7

SLAC 2422 klystron, standard body, Merdinian gun.

— — — — Electromagnet optimum field at 250 kV.

———— Permanent magnet (PM-9)

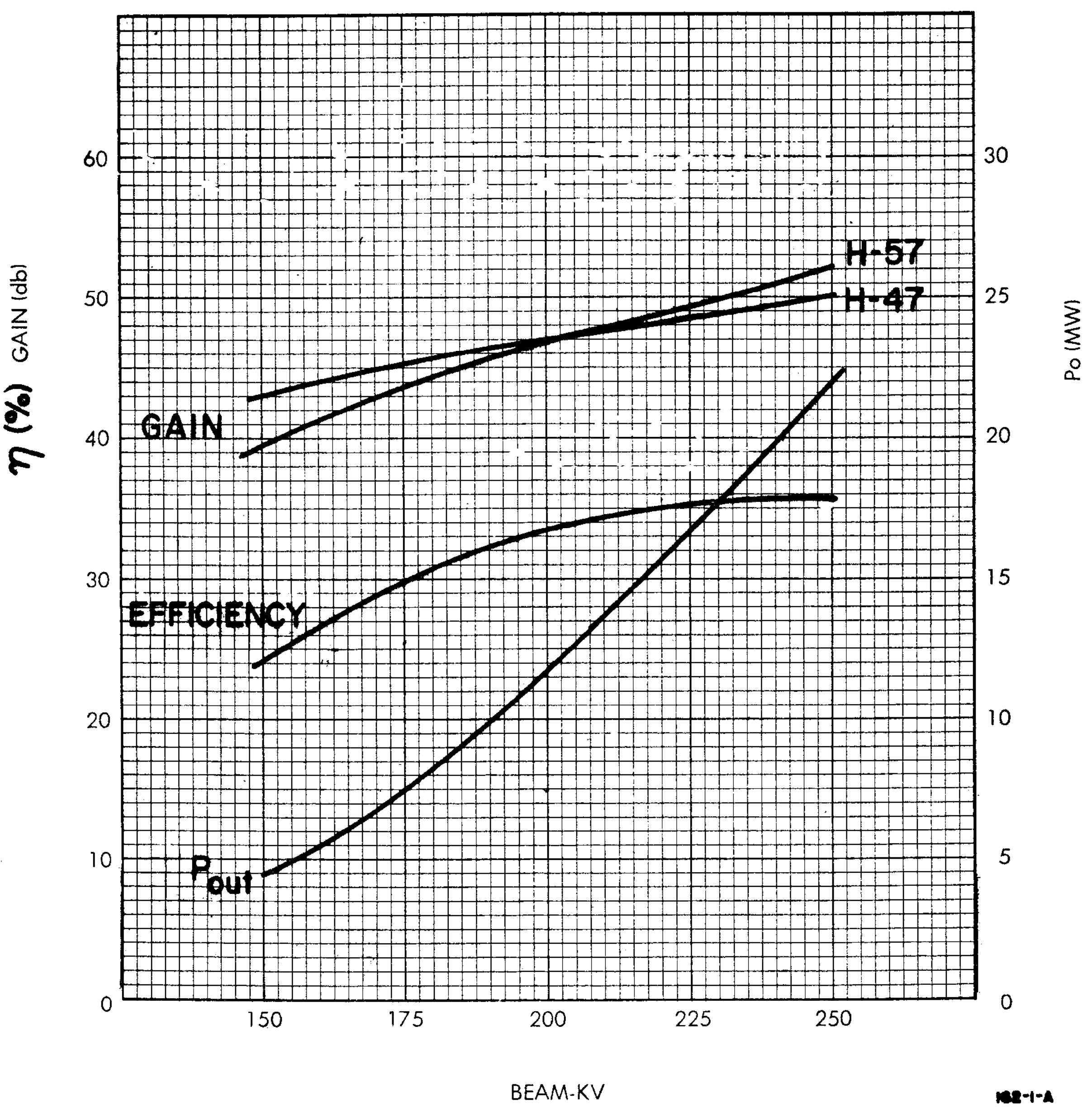
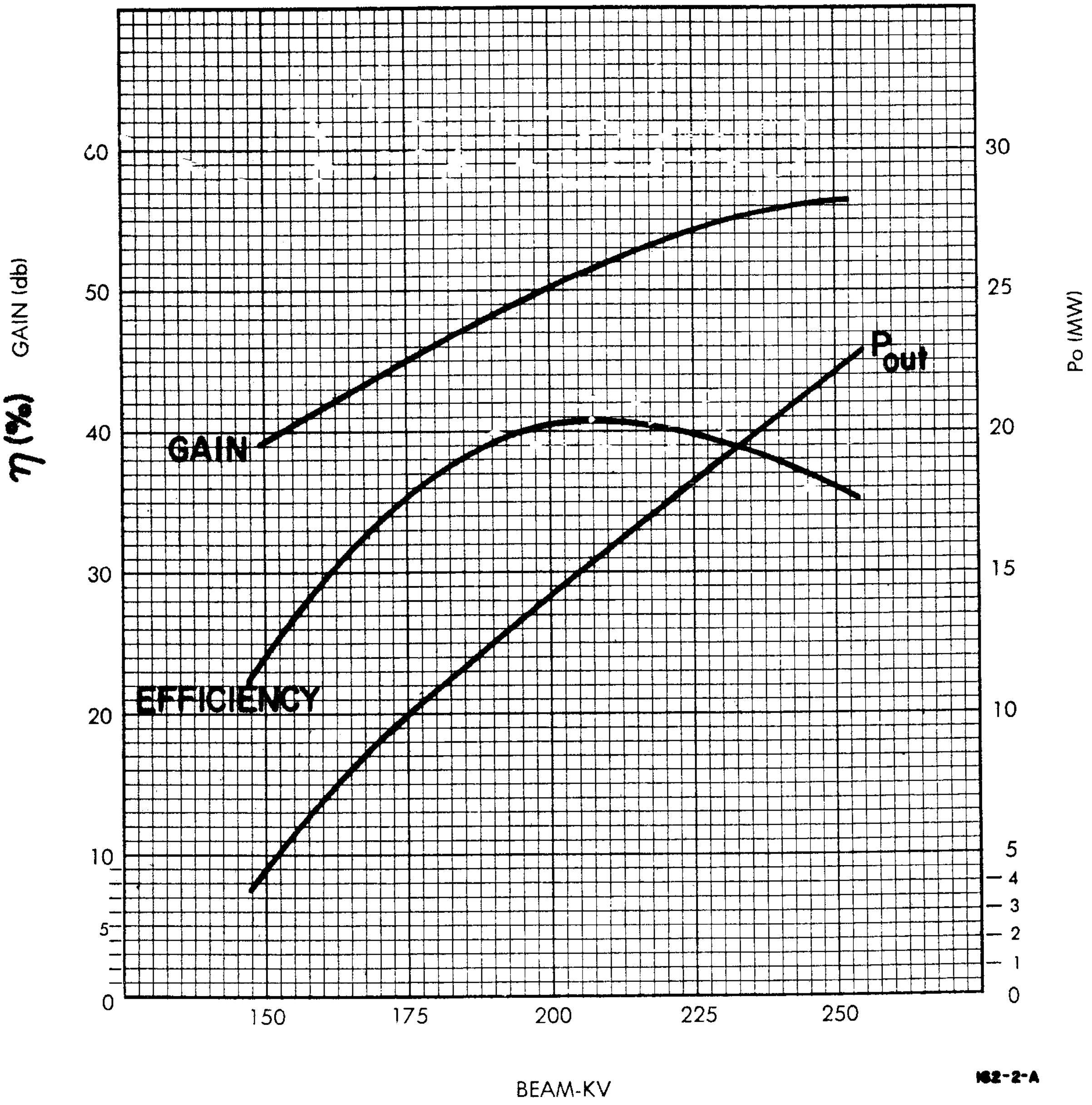


FIGURE 8

Stanford 2422 klystron, standard body, Merdinian gun, permanent magnet focusing. Comparison of different tubes in different magnets.



162-2-A

FIGURE 9

Stanford 2422 klystron, XM3 body, Merdinian gun. Performance in permanent magnet.

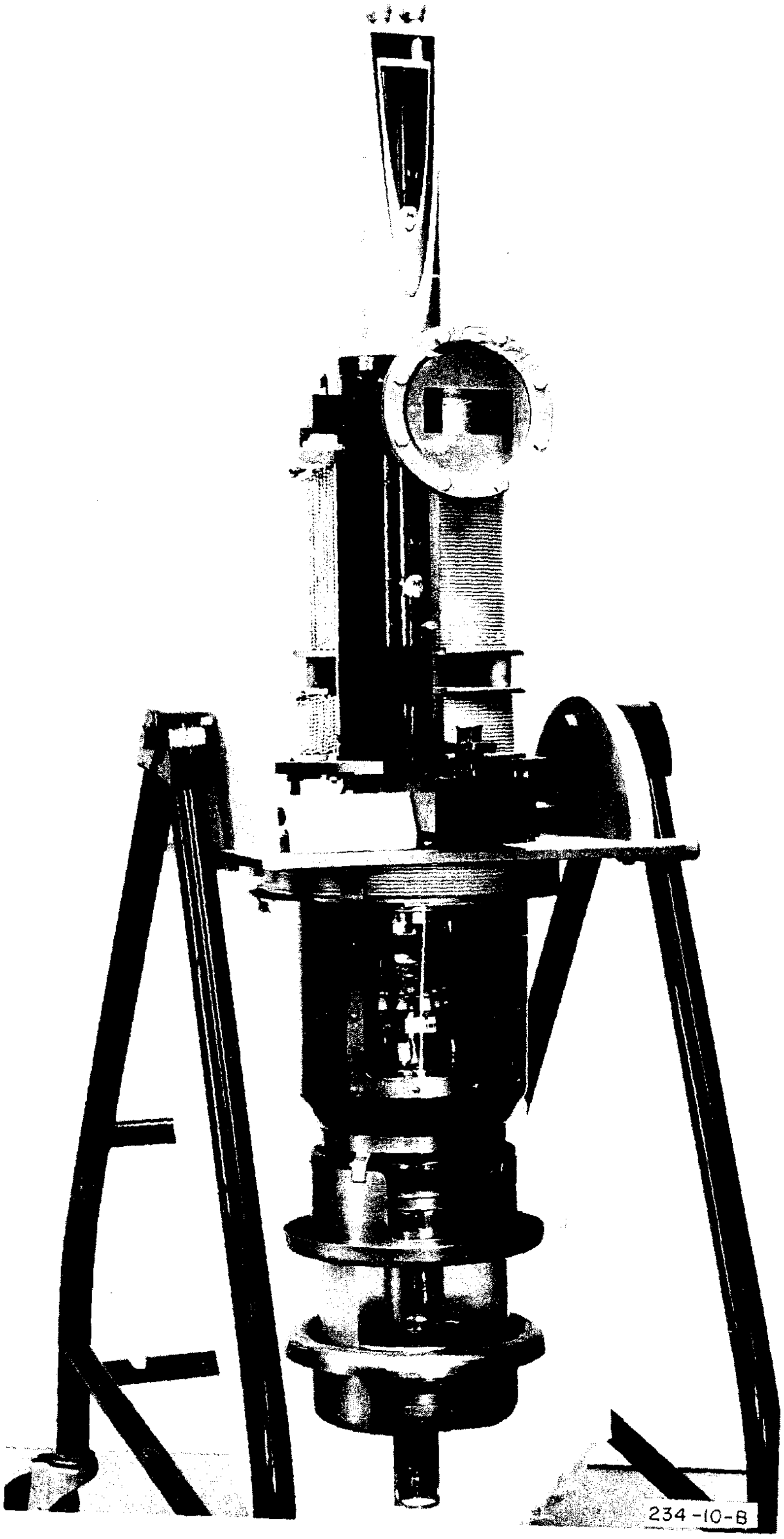


FIG. 10--Cutaway model of Stanford Mark III klystron.

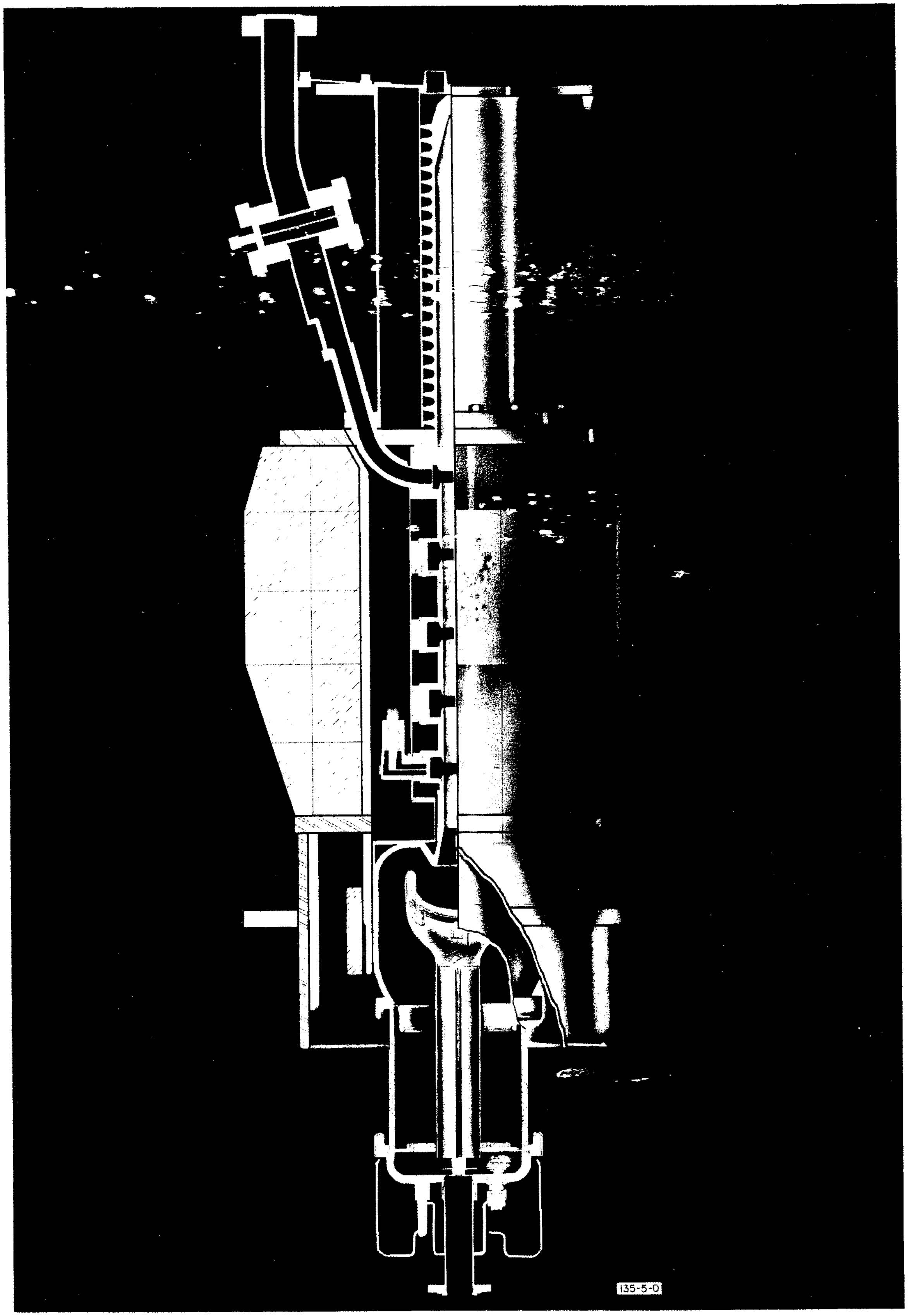


FIG. 11--Cutaway drawing of Stanford 2422 klystron.

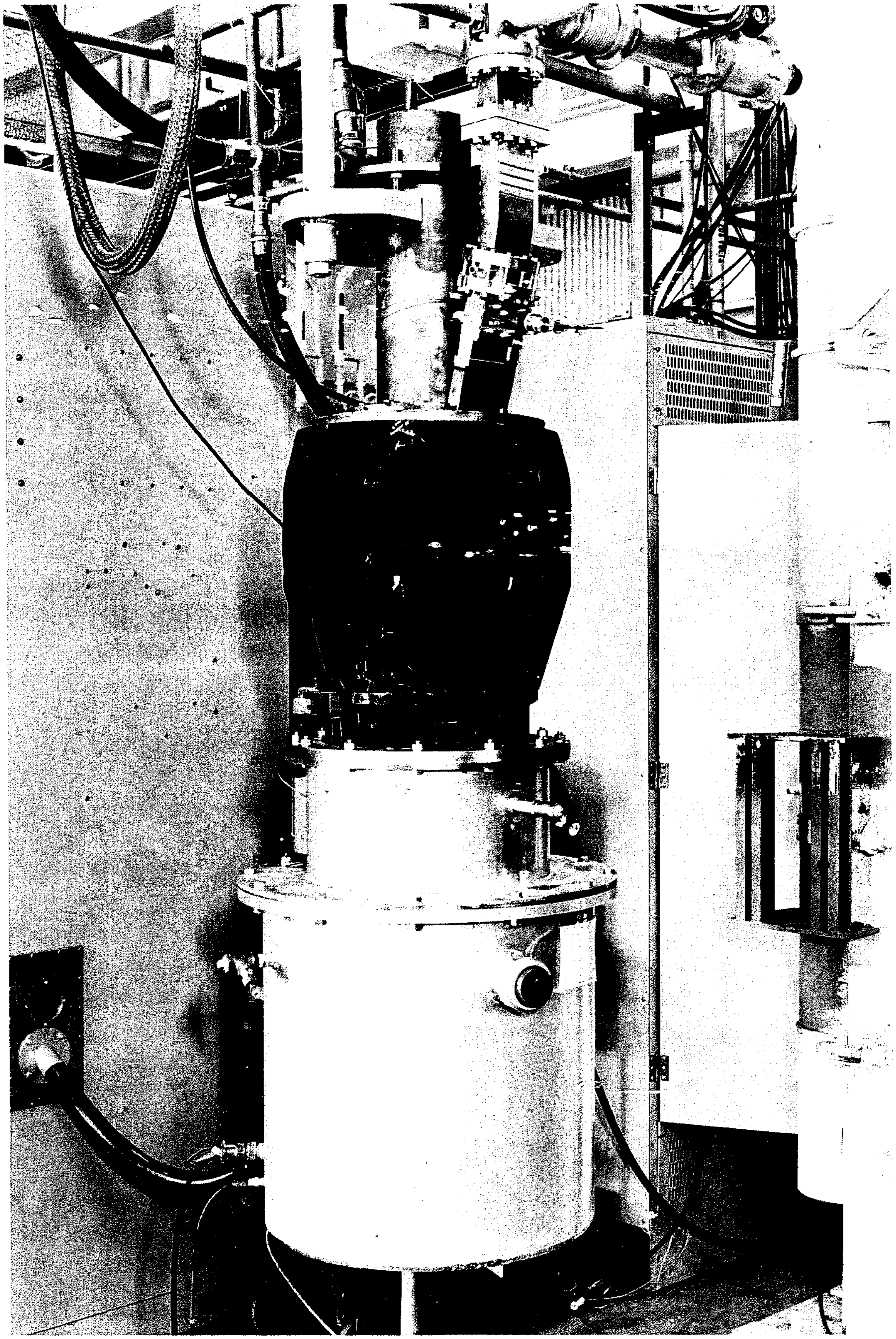


FIG. 12--Photo of Stanford 2422 klystron installed in mock-up.

234-12-A