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KLYSTRONS FOR THE STANFORD LINEAR ACCELERATOR CENTER*

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ABSTRACT

A two-mile-long linear accelerator has been built at Stanford University which uses 245 klystrons to produce an electron beam with an energy up to 20 GeV. Although most of the tubes used are being procured from industry, a major portion of the development work has been, and is still being, done at Stanford. We will review the important results of this work.

In general, the klystrons are designed to produce a minimum of 21 MW peak power with extremely stringent phase and amplitude stability performance requirements. They are focused by permanent magnets and operate up to 250 kV beam voltage with a microperveance of 2. During the past few years, gradual improvements in performance have been achieved by optimizing the bunching parameter and the output cavity coupling, and we have measured efficiencies approaching 45% in a permanent magnet. Permanent magnet structure limitations, field shaping and changes in the klystron design to reduce the magnetic field requirements will be discussed. The output window life has been improved by coating techniques developed to decrease single surface multipactor and reduce window operating temperature. Questions of coating stability will also be discussed.

Finally, the paper will touch on the initial results of statistical analysis of tube life as a function of operating experience.

I. INTRODUCTION

The Stanford Linear Accelerator Center has built a two-mile long linear accelerator. During initial tests of the accelerator in May 1966, a beam energy in excess of 18 GeV was achieved utilizing the power output of almost a full complement of 245 klystrons. These klystrons produce a minimum specified power output of 21 MW peak and 20 kW average when operated at 250 kV beam voltage, and are focused in permanent magnets. Their extremely stringent specifications have been published previously.[1] Although most of the tubes are being procured from industry, a major portion of the development work has been, and is still being, done at Stanford. The Stanford klystron development department's function is to achieve a more reliable and efficient klystron design which can be relayed to industry for evaluation and inclusion in future procurements. The results of our work from 1963 to the present are shown in Fig. 1. We have built two experimental tubes which produce more than 27 MW at 250 kV with permanent magnet focusing, with an efficiency of approximately 43%.

Output window failures still remain one of the major operating life problems. Although window coating has greatly improved window life, additional work is being done to improve the stability of the coating.

A brief review of tube performance will include the mean value of measured power output and an analysis of the information available to date on tube life.

II. DESIGN AND PERFORMANCE

The basic design[2,3,4] has been simplified by using a fixed-frequency tuned five-cavity klystron for fixed-frequency operation. Initially, the output was divided between two output waveguides, but improvements in window design and performance have allowed us to change the output to a single output window structure.

The gun initially used in this tube followed the Picquendar design;[5] this gun was later replaced by a gun design by Merdinian,[6] resulting in a beam diameter of approximately 0.8 inch. The same gun is still in use in all the Stanford tubes built at present with only a very minor modification in the button radius of curvature to compensate for thermal expansion.

The tube is designed to meet the basic requirements of 24 MW peak power output with a minimum gain of 50 dB at 2.856 GHz. To achieve these objectives the tube was designed as a five-cavity amplifier with the major design parameters listed in Table I below:

TABLE I

Design Parameters of SLAC 24-MW Klystrons

Beam Voltage	-- 250 kV
Beam Current	-- 250 A
Drift Tube Diameter	-- 1.125 inches*
Beam Diameter	-- 0.8 inch
γ_a	-- 0.777 radian
γ_b	-- 0.552 radian
Reduced Plasma Wavelength	-- 54 inches
Reduced Plasma Degrees per inch	-- 6.66
One Radian Gap	-- 0.488

*In the latest experimental tubes, the drift tube diameter was increased to 1-1/4 inches between the third and fifth cavity.

Table I (Continued)

Coupling Coefficient $\overline{M}_r^2$ (for one radian for buncher)	-- 0.383
G_B/G_O	-- 0.0627
R/Q Approx. for all Cavities	-- 80
Coupling Coefficient $\overline{M}^2$ (for one radian for output)	-- 0.707
Output Q Optimum	-- ~ 18
Small Signal Gain	-- ~ 60 dB

The resultant tube layout is shown in Fig. 2.

During the past few years gradual improvements in performance have been achieved by optimizing the bunching parameters, output coupling, and fitting the beam optics to the available permanent magnet focusing field by modifying the drift tube diameter. The drift distances have been changed gradually in successive designs, as indicated in Table II. The obvious design limitation of the SLAC klystron is determined by the maximum length over which a permanent magnet can produce a field adequate for beam focusing. Hence, the drift distances, L_{3-4} and L_{4-5}, have been determined by using Webber's analysis[7] with the necessary compromises for the overall length allowed by the permanent magnet. According to Webber's analysis, our drift distances are probably still not optimum, but they cannot be further increased because of the permanent magnet limitation.

The results obtained for the tubes from XM-1 to XM-7 are shown in Fig. 3, in which the power output as a function of beam voltage is plotted for tubes operating in an electromagnet with the magnetic field and the drive optimized at each voltage. Curve XM-1 gives the average performance of the few tubes built to these dimensions. Curve XM-3 gives the average of the measurements on ten tubes built to the same dimensions, and measured during the fourth quarter of 1964. Curve XM-7 gives the average of the last ten XM-7 tubes built at

TABLE II

Drift Distances in Inches

Drift Distance	XM-1	XM-2	XM-3	XM-7
L_{1-2}	3.0	2.875	2.894	2.894
L_{2-3}	3.0	3.000	2.857	2.857
L_{3-4}	3.5	4.250	4.842	4.568
L_{4-5}	3.5	3.750	3.726	4.000
TOTAL	13.0	13.875	14.319	14.319
Q_e Output	25-30	20-25	18-20	18-20
The reduced plasma wavelength is approximately 55 ins.				

Stanford. It is believed that the main improvement in performance between the XM-3 and XM-7 tube is caused by the change in drift distances.

In Fig. 4, we have plotted the average of the performances of the same ten XM-7 tubes, but now operated in a "standard" permanent magnet. The performance of the XM-3 in "standard" permanent magnets is very similar to that of the XM-7 tubes. It can be noticed that the loss in peak power from electromagnet to permanent magnet is less than 1 MW for the XM-3 tubes, but approximately 3 MW for the XM-7 tubes at 250 kV.

We have built several tubes which produced over 27 MW at 250 kV in electromagnets almost a year ago, but these klystrons seldom delivered more than 23 MW in a permanent magnet. The reason for this much greater decrease in power output is obvious upon analysis of the magnetic field plots (see Fig. 5). Curve 1 of Fig. 5 is the "standard" permanent magnet curve which closely approximates the optimum electromagnet focusing measured initially on tubes of the XM-1 and XM-3 variety. Optimum electromagnet performance was obtained with the XM-7 tubes with a field plot which approximates curve 2 of Fig. 5. With permanent magnets commercially available at present, it does not appear feasible to obtain fields similar to that of curve 2 in Fig. 5.

The high fields necessary near the third drift tube indicated that the electron beam was scalloping. Several klystrons were built with smaller beam diameters, but these klystrons performed identically to XM-7 tubes except that they required even higher magnetic field. A new approach was taken: to match the beam to the permanent magnet or even reduce the field requirements below what is available from permanent magnets. It appeared possible that, by increasing the drift tube diameters between the third and fifth cavities, a reduction of magnetic field requirements could be achieved without impairing the output gap coupling coefficient and the tube performance.

Accordingly, two experimental tubes (XM-12) were built with the third and fourth drift tube diameters increased from 1-1/8 inches to 1-1/4 inches, but with all other dimensions equal to those of the XM-7 tube. Upon test in electromagnets, both tubes exhibited performance essentially equal to that of the best XM-7 tubes (as shown by curve XM-12, Fig. 3), but the magnetic field requirements had been drastically reduced as indicated by curve 3 of Fig. 5. These tubes were then tested in permanent magnets which had been demagnetized from their standard value by approximately 100 gauss. The actual magnetic field plot is given by curve 4 of Fig. 5 and the average performance in permanent magnet of the two XM-12 experimental tubes is shown in Fig. 4. It can be seen that their performance in permanent magnets is substantially the same as in electromagnets (27.5 MW and 250 kV at an efficiency of over 43%).

A klystron similar to XM-12 but with penultimate and output cavity gaps reduced to 0.87 and 0.8 radian, respectively, has been built. The test results are not conclusive, due to poor tube vacuum.

Another approach which has been tried but has not so far proved satisfactorily repeatable is to build an extended interaction output cavity. The first tube with such an output cavity gave better performance than the XM-7 tubes at that time, but subsequent tubes were plagued by oscillations and instabilities which made them unsuitable for accelerator operation.

A. Output Windows

The output windows of tubes used on the Stanford Linear Accelerator operate into an evacuated load. As a result, some window problems are more severe in our application than in general usage of high power klystrons for the following reasons: (1) there is no convection cooling on the load side of the window, and (2) there is a possibility of single surface multipactor on both sides of the window.

The two main types of window failures observed on klystrons used at Stanford on linear accelerators have been dielectric failures, usually resulting in window puncture, and thermal failures, usually resulting in mechanical rupture of the ceramic.

It was reported previously[8,9] that titanium coating applied to both surfaces of the output window suppresses multipactor. By reducing the secondary emission coefficient of the ceramic, multipactor heating is effectively eliminated as a cause of thermal window failure. It is suspected that the coating may also alleviate the dielectric puncture problem by reducing the probability of charge build-up on the window surface. The coating used at Stanford is applied by sputtering titanium in an argon atmosphere at a pressure of approximately 100 microns. Based upon relative measurements made during the coating process with a crystal resonator acting as a microweighing device, coating thickness limits of 80 to 150 Å have been established.

The most frequent cause of failure on SLAC windows today is thermal failure, not because of multipactor but because of resistive loss in the coating layer. The titanium coating is not completely stable when exposed to high temperature during vacuum bake of the tube. Following application and subsequent exposure to air, the coating assumes an electrical resistivity of greater than 10^{12} ohms per square. However, during vacuum bake, resistance can drop to 10^{6} ohms or even less if the coating thickness is excessive. Even after cooling, the tube side window surface maintains a relatively low resistance which may contribute significantly to overall window heating. Only when the tube side of the window is exposed to air (as for instance, during rework) does the coating resistivity regain its initial high value. If the window is then rebaked, the resistivity will drop even lower than during the first bake. Our experience with windows baked more than once has shown that such windows will most probably fail under thermal stress during full power tube operation.

Many of the window losses experienced by some of our klystron vendors also may be caused by coating instability. We have found that titanium-base coatings can be lost or reduced to a metallic state during hydrogen braze cycles as well as during vacuum bake. Comparison studies at SLAC have indicated that coatings applied by evaporation are even less stable than sputtered coatings. It appears at present that there is a critical dependence between the oxygen content of a coating and its stability. The most successful coatings, whether sputtered or evaporated, have been applied in systems with a substantial amount of residual oxygen available for reaction with the titanium being deposited. Controlled stability is now being sought by introducing a measured amount of oxygen to the coating vessel mixed in with the argon. The results of initial tests of oxygen-enriched coating have been encouraging but not yet conclusive.

Comparative evaluations of window coatings as a function of oxygen content, as well as of coating thickness and other coating control variations, are now being made by means of a "double-window" test technique. Two standard klystron windows are joined by a short section of waveguide which is evacuated by an independent ion pump. The entire assembly is tested at high power in the resonant ring before and after exposure to a tube bake. Temperature data from the first few double window tests have verified that vacuum bake causes high window operating temperatures, that exposure to air essentially reverses the effect of the bake, and that a second bake produces much more pronounced deterioration of the coating than does the first.

We are beginning work on the evaluation of other window coating techniques and materials. Evaporation and rf sputtering methods will be compared with our present reactive sputtering technique. The effects of gases absorbed during and after the coating are being evaluated, with particular emphasis on oxygen. It is not clear that titanium is the best coating material since its oxides are rather unstable under vacuum bake and other high-temperature cycles. Other low secondary emission films are being considered. Only tungsten carbide has been tested to date. Secondary emission characteristics of this material are good, but early tests show no apparent advantage over titanium with regard to stability.

There is no question that coated windows have a much better chance of long life than uncoated windows on high power klystrons operated into an evacuated load. The fact that window failures still occur on coated ceramics points to the necessity for continued coating studies, to find ways of increasing coating stability through all the conditions actually encountered in tube fabrication and operation.

B. Operating Experience

A total of almost 370 tubes have been accepted from three outside vendors, meeting the same electrical and mechanical specifications. Tubes from a given vendor are interchangeable with the permanent magnets supplied by that vendor, although they are not interchangeable with magnets from other vendors.

The mean of the peak power output measured for the last 20 tubes accepted from each of the three vendors is 12.5 MW at 200 kV and 22.2 MW at 250 kV. Hence, the tube power output is well above the acceptance test specification. The values are almost exactly the same as the average measured on SLAC XM-7 klystrons.

In the actual use of the accelerator for physics research, the beam energy is expected to vary from 10 to 20 GeV and the repetition rate from 60 to 360 pps. It is possible to achieve the required beam energies by various combinations of number of klystrons and operating level, since the beam energy can be expressed approximately as:

$$E = 20n \times \sqrt{P_k}$$

where E is the beam energy in MeV, n is the number of klystrons contributing rf energy, and P_k is the peak power per klystron in megawatts.

Since the actual operating cost of the machine will be greatly affected by the klystron replacement costs, a special test (endurance run) was initiated in April and ended on August 15, 1966, in an attempt to obtain some information on tube life and equipment reliability as a function of operating level. Seven pairs of sectors (8 tubes per sector, i.e., 112 klystrons) have been operated under substantially constant conditions of both beam voltage and repetition rate for 130,000 socket hours. The approximate operating conditions, the average number of accumulated hours per socket during the endurance run, and the number of klystron failures under the different operating conditions with the average life at the time of failure are given in Table III.

TABLE III

Klystron Endurance Run Results

Sector Pair	Operating Level: Reference Voltage	Klystron Beam Voltage	Klystron Peak Output Power (MW)	Repetition Rate (pps)	Average Operating Hours per Socket	Cumulative Klystron Failures	Average Life at Failure
3/4	115	240-250	19-22	60	1175	1	690
5/6	115	240-250	19-22	360	1050	6	270
7/8	105	220-230	16-18	60	1200		
9/10	105	220-230	16-18	180	1140*		
13/14	105	220-230	16-18	360	1135	2	920
15/16	90	195-205	11-14	60	1200	1	595
17/18	90	195-205	11-14	360	1190		

*This pair of sectors began the run approximately 60 hours after the others.

As of the end of March 1967, a total of approximately 687,000 plate hours had been accumulated on the sockets in the Klystron Gallery, with a total of 104 failures. Table IV shows the overall klystron usage and failures experience to date. Approximately 30% of these failures were caused by output window failures and approximately 50% were caused by tube gassiness, as evidenced by excessive arcing, pulse break-up, pulse droop and/or oscillations; the other failures were connected with either high voltage seal punctures or miscellaneous leaks or cathode problems. It is suspected that a number of the vacuum failures should really be considered as shelf life failures; during the initial turn-on period of the machine, many sockets were left inoperative for months after about 100 hours of operation. Microleaks or virtual leaks could have rendered the tubes inoperative after a shelf life of several months.

TABLE IV

Klystron Usage and Failures

Dates	Operating Hours		Quarter		Cumulative	
	Quarter	Cumulative	Number	Avg. Life at Failure	Number	Avg. Life at Failure
To 12/31/65		27,000			10	297
To 3/31/66	11,000	38,000	13	252	23	272
To 6/30/66	118,000	156,000	16	234	39	256
To 9/30/66	127,000	283,000	14	594	53	350
To 12/31/66	176,000	459,000	23	1070	76	575
To 3/31/67	228,000	687,000	28	1670	104	860

The average life of the tubes at the time of failure was approximately 470 hours for those tubes which failed during the endurance run, and approximately 860 hours for all tube failures. In principle, it should be possible to predict a mean time to failure for all tubes on the basis of the information available to date. However, a plot of the failures on probability paper indicates a heavy preponderance of early failures which casts doubts on the validity of the analysis. We can say that the average operating time of all tubes on the machine is almost 2400 hours. Figure 6 shows the life distribution of the klystrons on the linac at the end of March, 1967.

Since the average number of operating hours of the tubes now in operation is approximately three times higher than the average life of the tubes which have failed to date, and since the number of failures is approximately 8% of the sample for the endurance run and 30% for the total failures, it again follows that many failures observed up to now must be considered as early failures. Statistical analysis indicates that the MTTF under overall operating conditions is probably in excess of 3500 hours, but insufficient data is available to predict the MTTF under the specific operating levels of the endurance run.

III. CONCLUSIONS

The evidence to date indicates that permanent-magnet-focused, high peak power klystrons have potential life expectancies equal to that of the usual electromagnet-focused klystron operating in military systems at lower power levels. The fact that only ten failures were observed for 130,000 socket hours of the endurance run suggests that many of the other failures observed were of the early failure variety and that the tube MTTF may well exceed 3500 hours.

It is particularly encouraging to know that vendors have been capable of supplying reliable klystrons for operation at these power levels with a mean peak power output in excess of 22 MW. The experimental work done at Stanford indicates that the tube design can be further improved to increase the available output power by at least 10 to 15%. Similarly, we expect that additional studies will result in improvements of the output window to further increase the tube life and reliability.

REFERENCES

1. J. V. Lebacqz, "High Power Klystrons," IEEE Transactions on Nuclear Science, Volume NS-12, No. 3 (June 1965).
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. R. Metivier, "Les Klystrons Amplificateurs de Grande Puissance de la Compagnie Francaise Thomson-Houston," Rev. Tech CFTH No. 32 (February 1960).
5. 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).
6. 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 (September 1964).
7. S. E. Webber, "Large Signal Analysis of the Multi-Cavity Klystron," G. E. Research Lab Report No. 58-RL-1897 (January 1958).
8. J. Jasberg and J. V. Lebacqz, "High Power Microwave Windows," Proc. Fifth International Conference on Hyperfrequency Tubes, Paris (September 1964).
9. R.Bierce, W. R. Fowkes, and J. H. Jasberg, "Window Materials Design and Properties for Use in High Power Klystrons," IEEE Transactions on Nuclear Science, Volume NS-12, No. 3 (June 1965).

LIST OF FIGURES

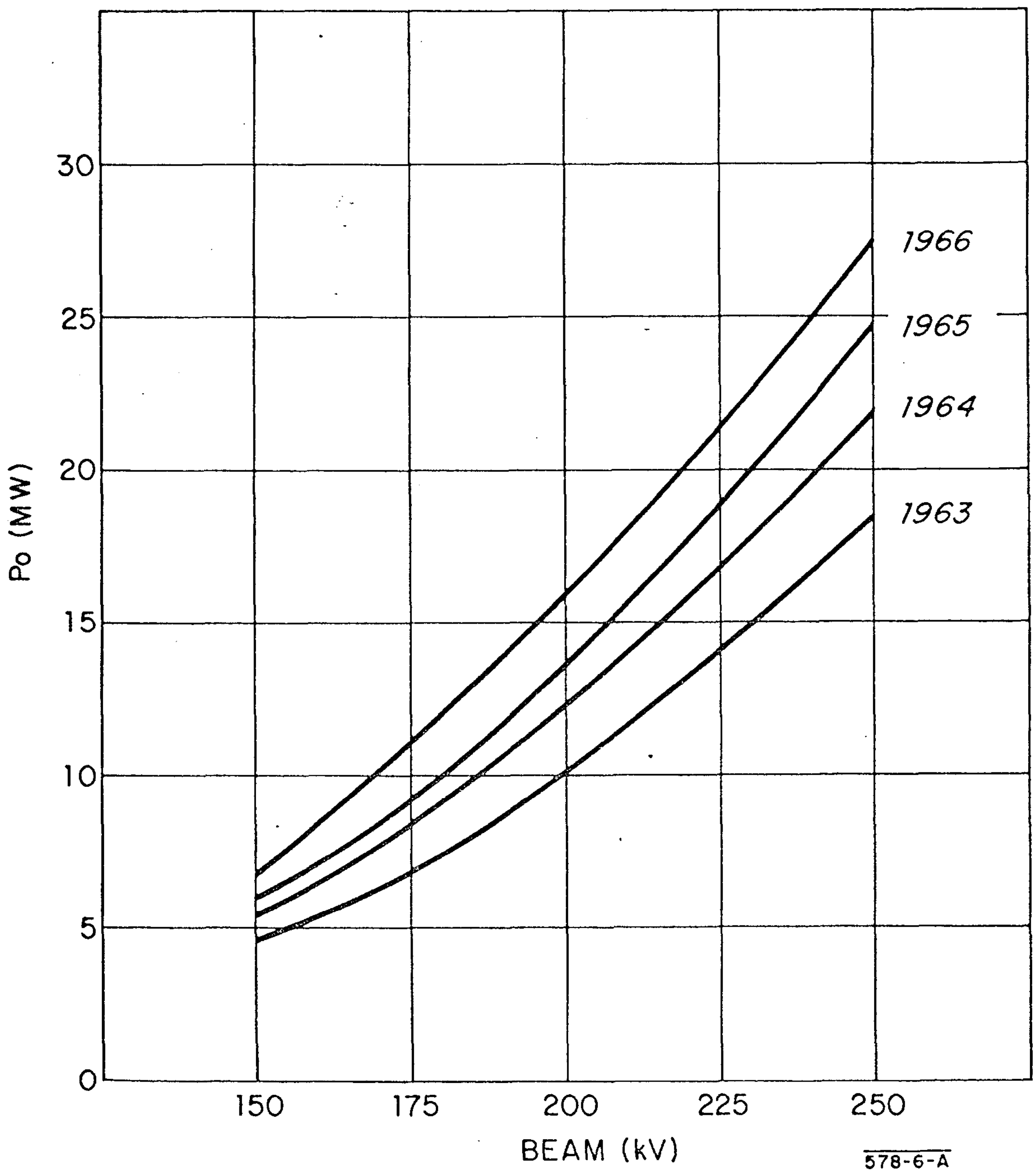
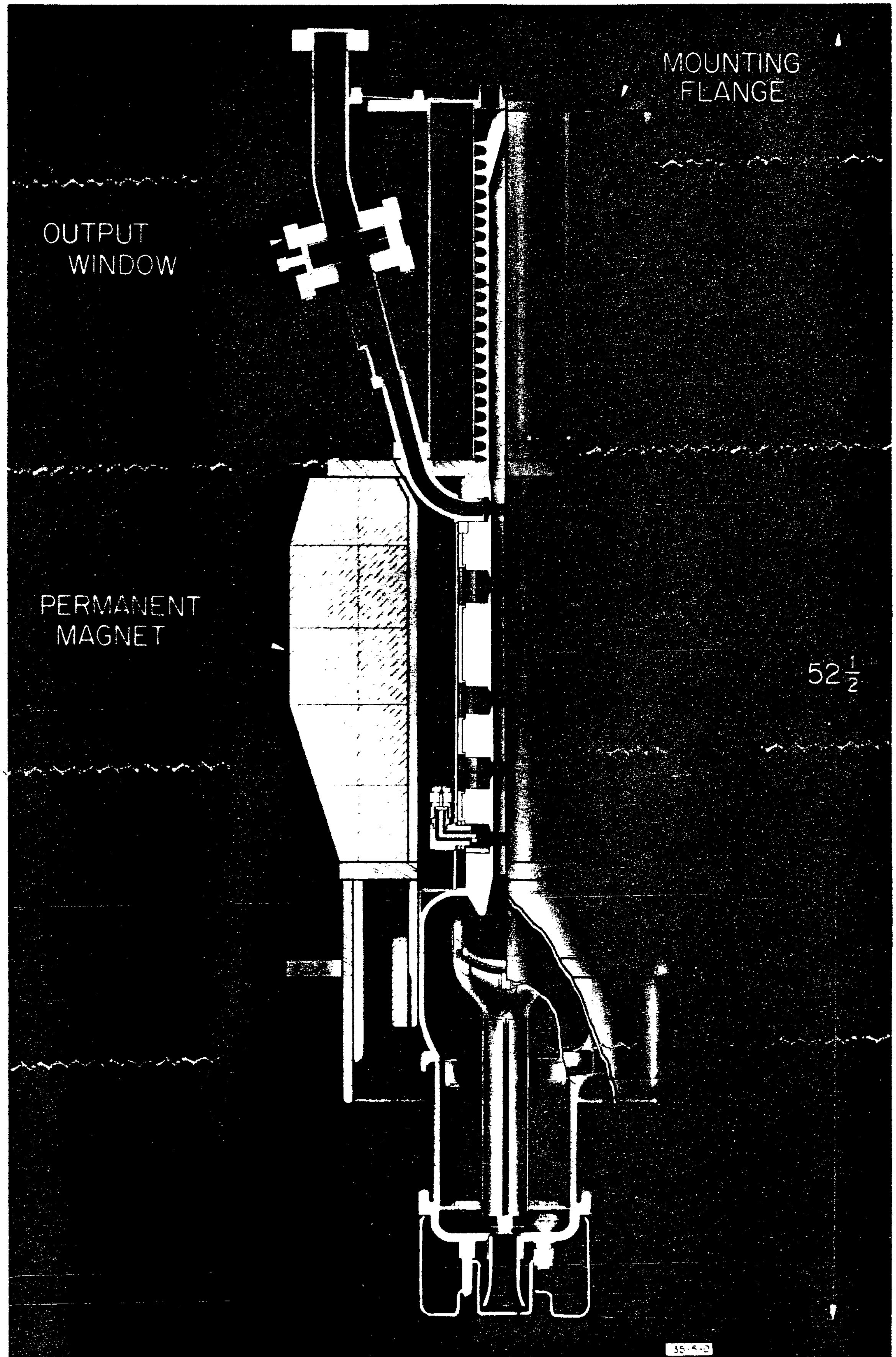


FIG. 1--COMPARISON OF SLAC KLYSTRON PERFORMANCE IN ELECTROMAGNET. DRIVE AND FOCUS OPTIMIZED AT EACH VOLTAGE.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MAGNET
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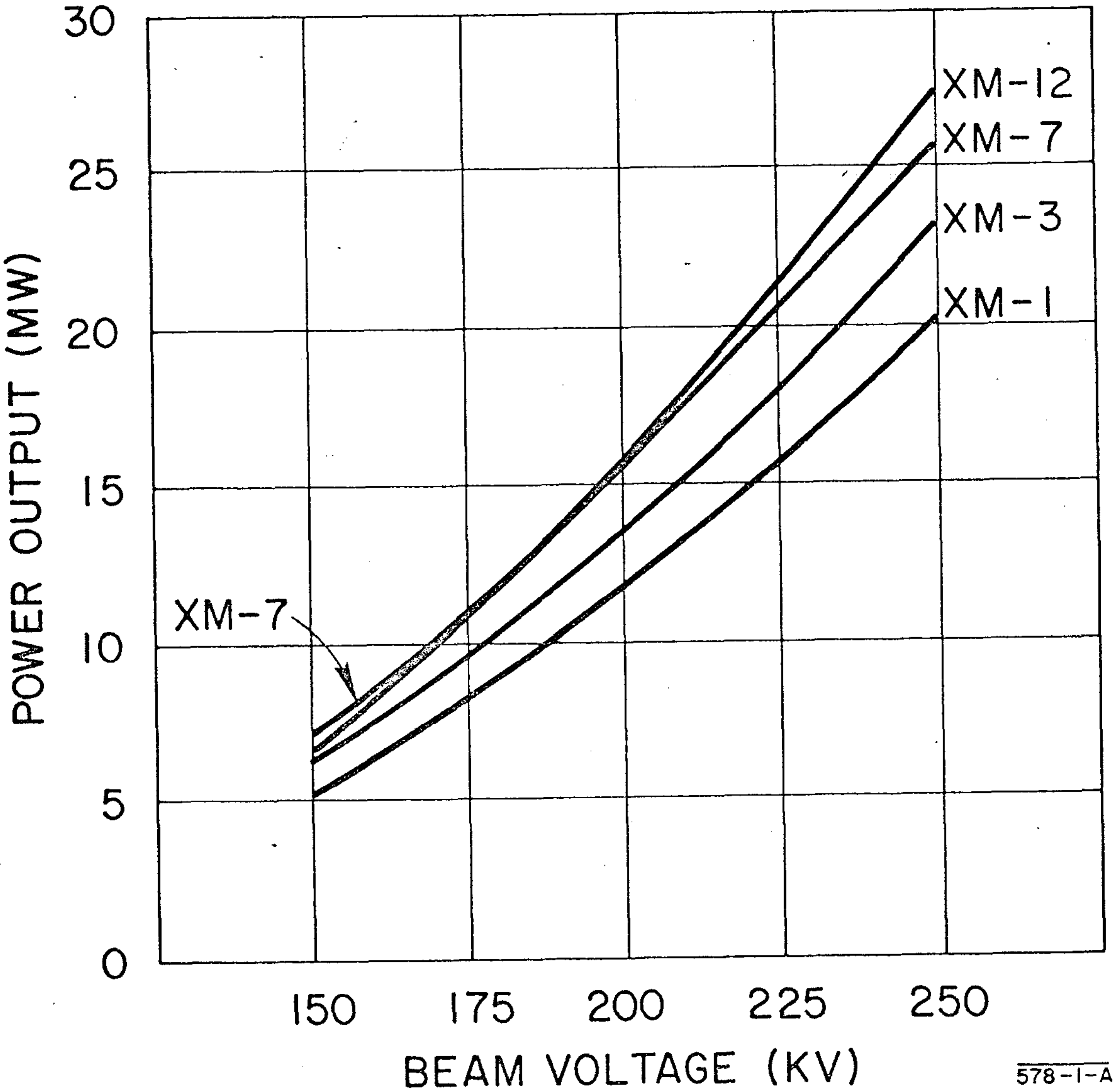

FIG. 3-- STANFORD KLYSTRON PERFORMANCE IN ELECTROMAGNET. DRIVE AND FOCUSING OPTIMIZED AT EACH VOLTAGE.

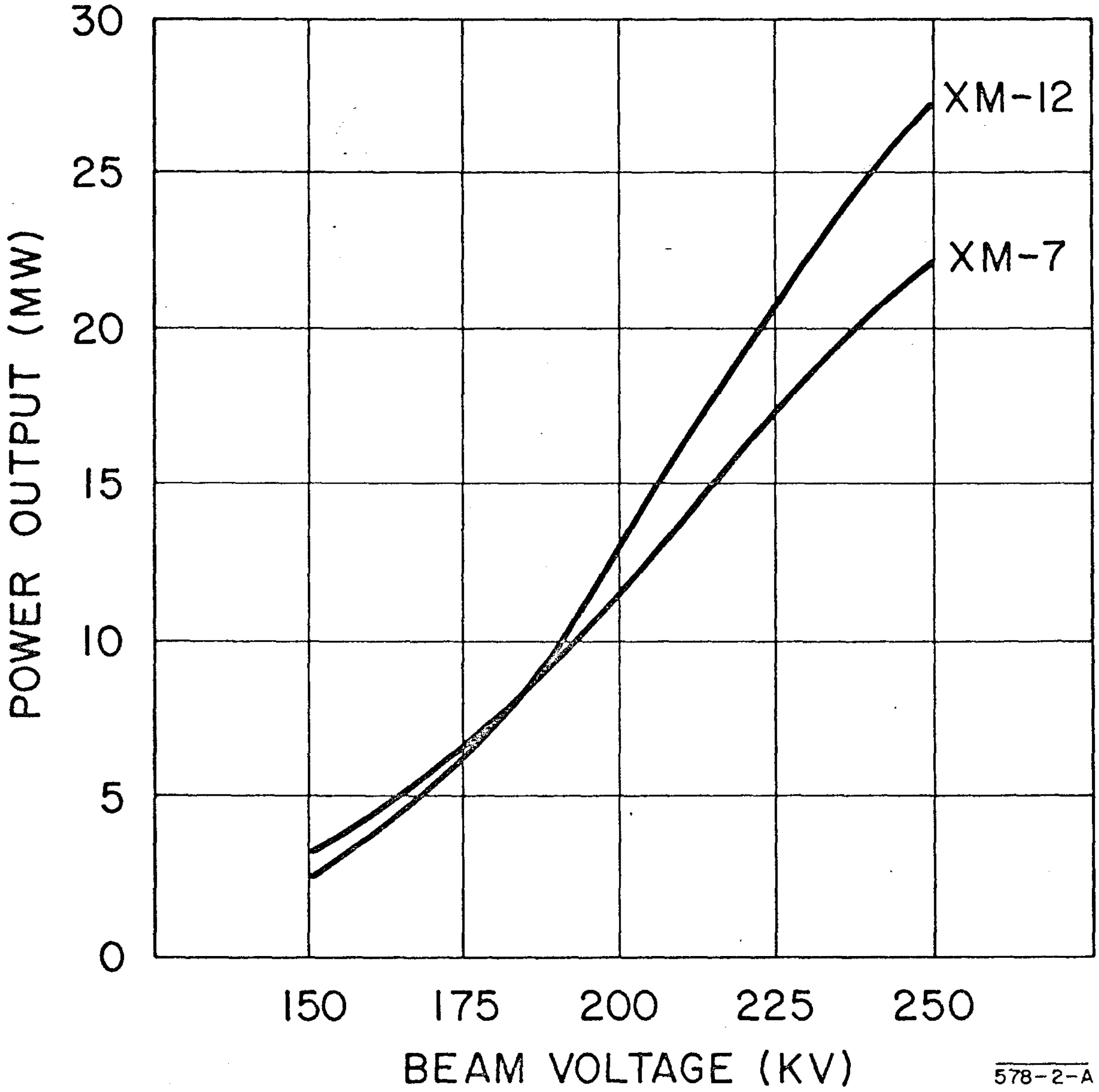

FIG. 4 -- STANFORD KLYSTRON PERFORMANCE IN PERMANENT MAGNETS

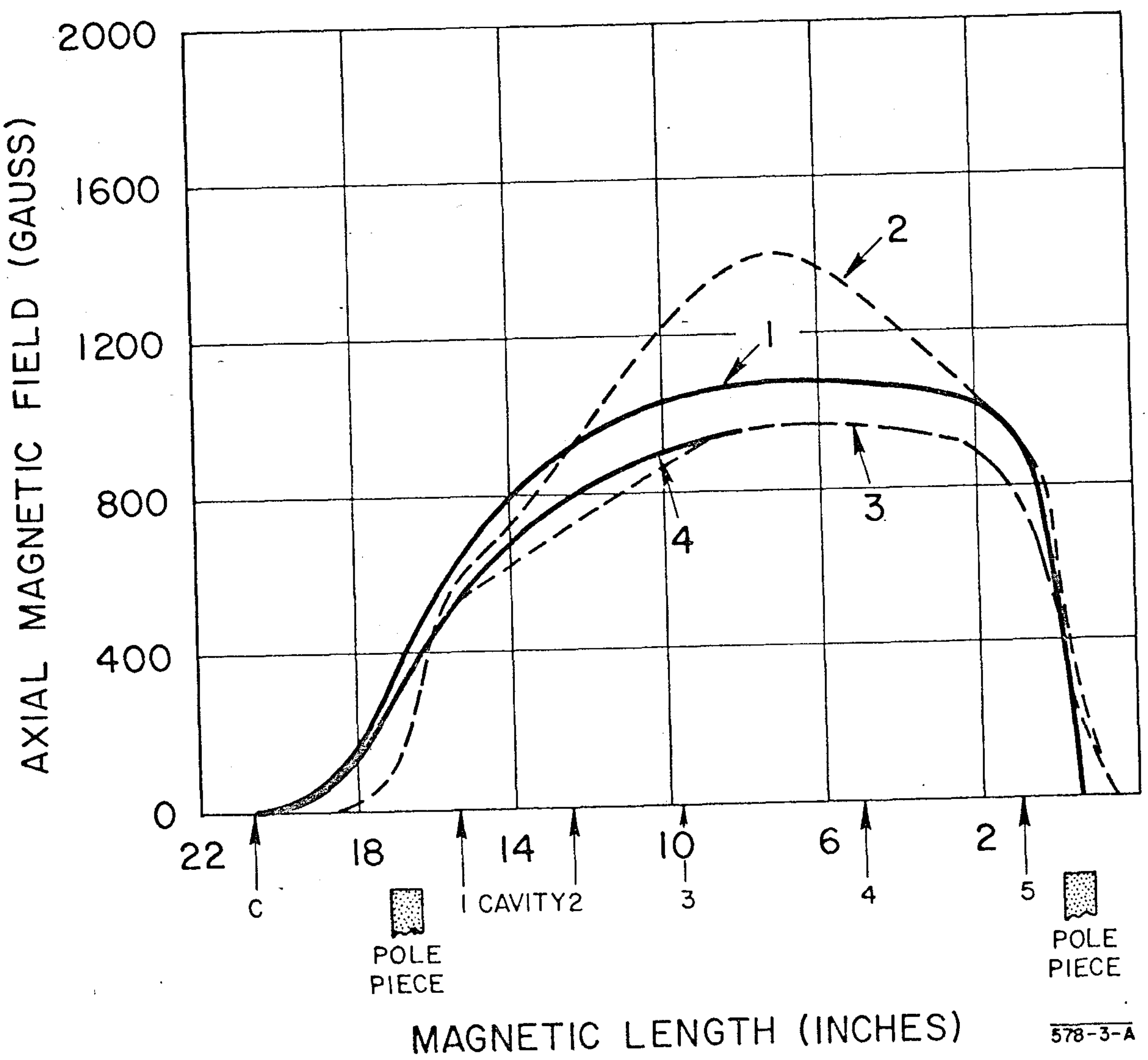

FIG. 5--AXIAL MAGNETIC FIELDS FOR STANFORD KLYSTRONS
1-"STANDARD" PERMANENT MAGNET FIELD
2-ELECTROMAGNET FIELD FOR XM-7 AT 250 kV
3-ELECTROMAGNET FIELD FOR XM-12 AT 250 kV
4-PERMANENT MAGNET FIELD FOR XM-12

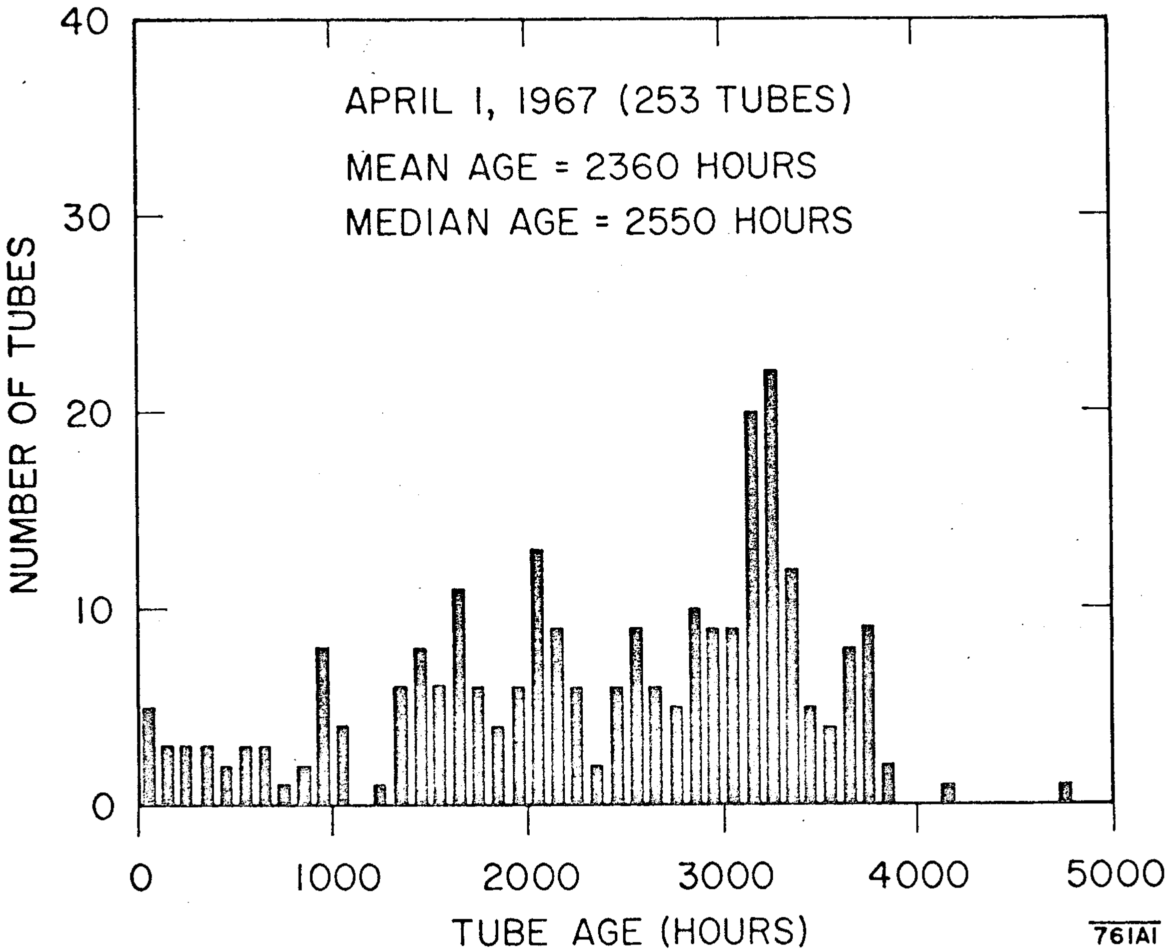

FIG. 6 -- KLYSTRON AGE DISTRIBUTION (ALL VENDORS) IN 100-HOUR INCREMENTS.