SLAC-PUB-208
August 1966

KLYSTRONS FOR THE STANFORD LINEAR ACCELERATOR CENTER*

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Introduction. The Stanford Linear Accelerator Center has built a two-mile long accelerator which derives its radio frequency energy from 245 pulsed S-band klystrons. These klystrons produce a minimum of 21 MW peak and 20 kW average power at 250 kV beam voltage when focused in permanent magnets; their specifications have been published previously.[7] During initial tests of the accelerator in May, 1966, a beam energy in excess of 18 GeV was achieved with essentially the full complement of klystrons.

Since the last papers published on the design and performance of the Stanford tubes, additional development work has been carried out at Stanford to further improve the performance. 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%.

One of the major contributing causes of tube failures remains the output window. Additional work is being done to improve the coating techniques and understand the reasons for coating instabilities which appear to be a contributing factor to window failures.

The tubes in operation at Stanford have for the most part been purchased from commercial sources. A brief review of tube performance will include the mean values of measured power output and an analysis of the information available to date on tube life.

Design and Performance. Because the tube is to operate at a fixed frequency, the basic design has been simplified by using a fixed tuned five-cavity klystron. Initially, the output was divided between two waveguides, but improvement in window performance allowed us to redesign for single output.

The gun initially used in this tube followed the Picquendar design[3]; this gun was later replaced by a gun design by Merdinian, resulting in a beam diameter of approximately 0.8 inch. The same gun is still in use in all the tubes built at present with only a very minor modification in the button radius of curvature to compensate for thermal expansion.

The major changes in the tube design in the past few years have been in the modification of gap spacings and drift distances to optimize tube performance. The output gap length has been decreased to approximately 0.475 inch, and the drift distances have been changed gradually in successive designs, as indicated in Table 1. As seen from Table 1, the output cavity Q has been gradually decreased to what appears to be the optimum value of approximately 20. The total drift distance from input to output has been increased as indicated in Table 1 without having to change the overall length of the magnetic field by reducing the length from the anode to the first cavity and that from the output cavity to the collector.

The changes in drift distances between cavities 3 & 4 and 4 & 5 were determined on the basis of the vector analysis for optimum bunching and corrected

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*Work supported by U. S. Atomic Energy Commission.

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(Presented at the Sixth International Conference on Microwave and Optical Generation and Amplification, Cambridge, 12-16 September 1966)

by experimental evidence from the tubes built. The results obtained for the tubes from XM-1 to XM-7 are shown in Fig. 1, in which the power output as a function of beam voltage is plotted for tubes operating in electromagnet with the magnetic field and the drive optimized at each voltage. The curve XM-1 gives the average performance of the few tubes built to these dimensions. The 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. The curve XM-7 gives the average of the last ten XM-7 tubes built at Stanford.

In Fig. 2, 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. In fact, we have built XM-7 tubes which produced power output in excess of 27 MW in electromagnets, but only approximately 22 MW in permanent magnets.

The reason for this much greater decrease in power output is obvious upon analysis of the magnetic field plots (see Fig. 3). Curve 1 of Fig. 3 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. 3. With permanent magnets commercially available at present, it does not appear feasible to obtain fields similar to that of curve 2 in Fig. 3.

The high fields necessary near the third drift tube indicated that the electron beam was scalloping. 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. 1), but the magnetic field requirements had been drastically reduced as indicated by curve 3 of Fig. 3. 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. 3 and the average performance in permanent magnet of the two XM-12 experimental tubes is shown in Fig. 2. It can be seen that their performance in permanent magnets is substantially the same as in electromagnets.

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 XM-7 tubes at that time, but subsequent tubes were plagued by oscillations and instabilities which made them unsuitable for accelerator operation. In an effort to understand the potential performance improvement to be achieved by extended interaction cavities, a tube was built with two output cavities separated by approximately 1.2 inches gap to gap; in other respects, the body was identical to an XM-7. The performance of the tube indicated that 4% to 10% power output might be salvaged from the second output cavity if the first were optimally coupled to the beam. The results are shown in Fig. 4 (electromagnet optimum focused and drive at each level). The most significant result seems to be a much broader saturation curve; that is, as the drive is decreased the power output from the first output cavity decreases in a standard fashion, but the power output from the second cavity increases. Also, if the first cavity's load is mismatched, additional power is salvaged from the second cavity.

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 stringent 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[5,8] 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.

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, most of which are oxides or nitrides of Period 4 elements. 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.

Operating Experience. A total of almost 300 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. Figure 5 is a photograph of klystrons supplied by the different vendors and built by SLAC, showing them mounted in pulse transformer tanks and ready for installation in the Klystron Gallery.

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) 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 2.

As of the middle of August 1966, a total of approximately 225,000 plate hours had been accumulated on the sockets in the Klystron Gallery, with a total of 47 failures. Approximately 40% of these failures were caused by output window failure and approximately 50% were caused by tube gassiness as evidenced by excessive arcing, pulse breakup, pulse droop and/or oscillations; the remainder of the failures were either high voltage seal punctures or collector failures. 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.

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 340 hours for all tube failures. In principle, it should be possible to predict a MTTF 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, however, that the average operating time of the tubes in the endurance run sockets was in excess of 1200 hours (these tubes had some operating hours prior to the beginning of the endurance run), and that the average operating time of all tubes on the machine is approximately 850 hours.

Since the average number of operating hours of the tubes now in operation is approximately two and a half 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 15% 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 between 1700 and 3500 hours, but insufficient data is available to predict the MTTF under the specific operating levels of the endurance run.

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 at similar 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 37 failures observed were of the early failure variety and that the tube MTTF may well exceed 2500 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.

This work is supported by the U. S. Atomic Energy Commission.

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Table 1

Drift Distances in Inches

Drift Distances	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	4.668
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 inches.				

Table 2

Klystron Endurance Run Results

Sector Pair	Operating Level				Average Operating Hours per Socket	Cumulative Klystron Failures	Average Life at Failure
	Reference Voltage	Klystron Beam Voltage	Klystron Peak Output Power (MW)	Repetition Rates (pps)			
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.

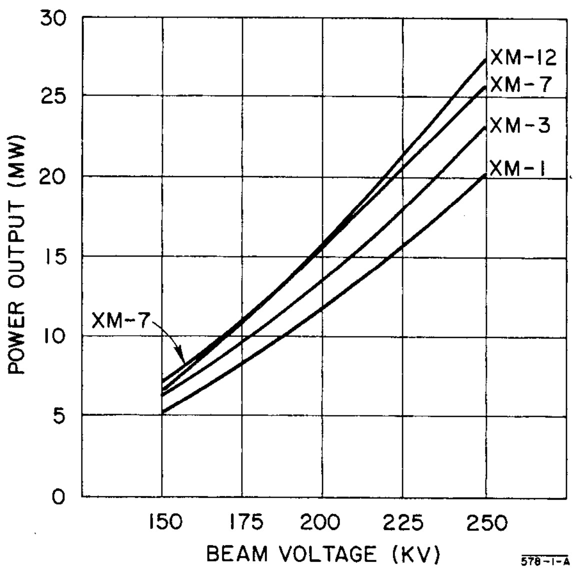

FIG. 1 -- STANFORD KLYSTRON PERFORMANCE IN ELECTROMAGNET. DRIVE AND FOCUSING OPTIMIZED AT EACH VOLTAGE.

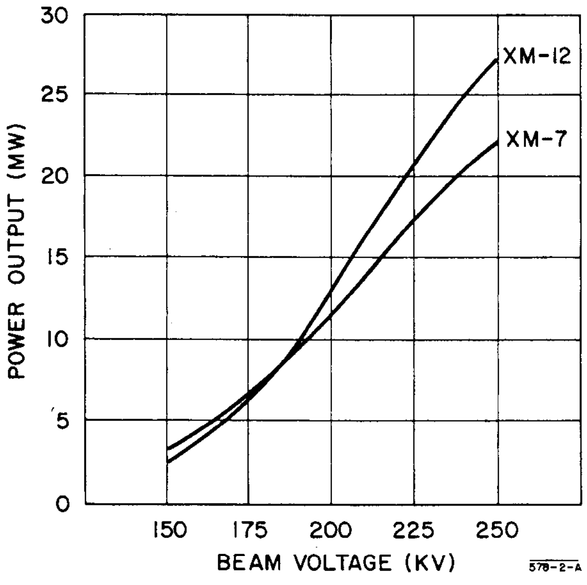

FIG. 2 -- STANFORD KLYSTRON PERFORMANCE IN PERMANENT MAGNETS

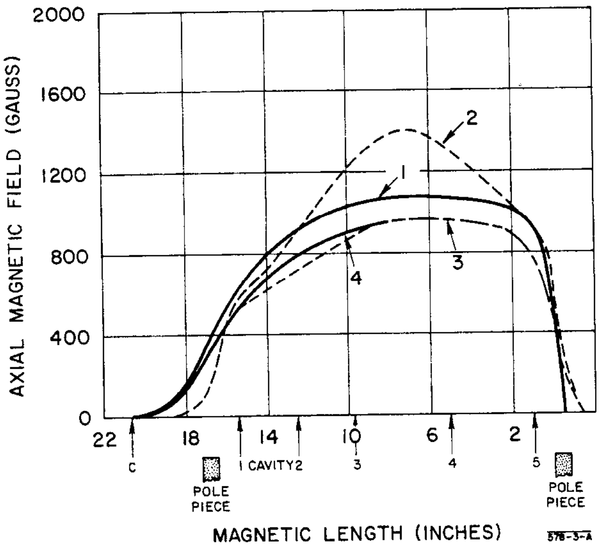

FIG. 3--AXIAL MAGNETIC FIELDS FOR STANFORD KLYSTRONS
1-"STANDARD" PERMANENT MAGNET FIELD
2-ELECTROMAGNET FIELD FOR XM-7 AT 250 kV
3-ELECTROMAGNET FIELD FOR XM-12 AT 250 kV
4-PERMANENT MAGNET FIELD FOR XM-12

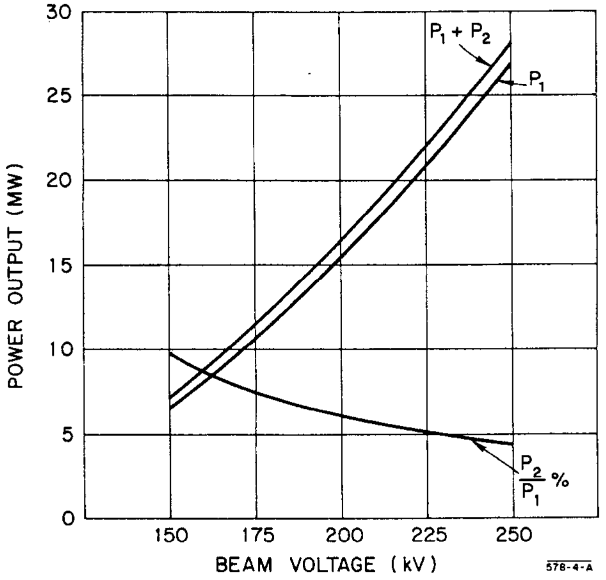

FIG. 4--EXPERIMENTAL DOUBLE OUTPUT KLYSTRON PERFORMANCE

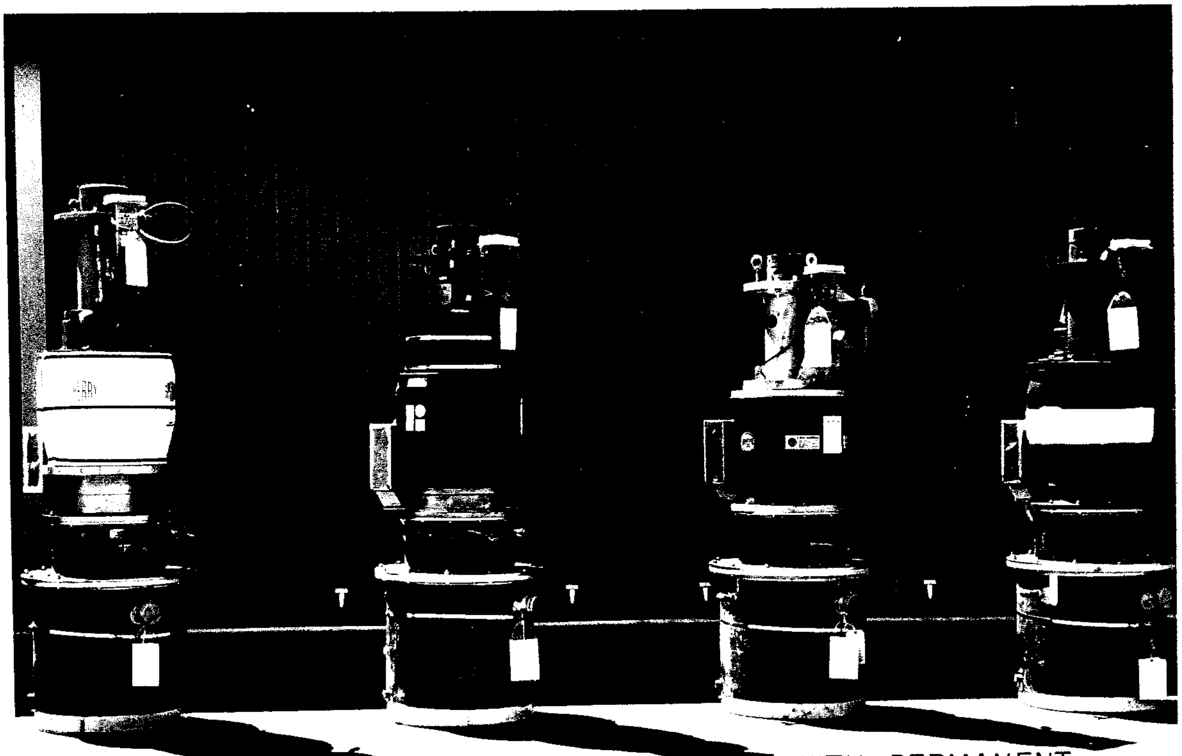

FIG. 5--PHOTOGRAPH OF STANFORD KLYSTRONS WITH PERMANENT MAGNETS AND PULSE TRANSFORMER TANKS READY FOR INSTALLATION

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