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HIGH POWER KLYSTRON DEVELOPMENT AT THE STANFORD LINEAR ACCELERATOR CENTER*

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1. Introduction

The Stanford Linear Accelerator has been in operation since July of 1966. A beam of energy of 20 GeV is derived from 245 permanent magnet focused 2856 MHz klystrons operating at 245 kV. The klystrons were designed to produce 21 MW minimum peak power output and 20 kW average power output at a beam voltage of 250 kV.

Recent physics demands have made it desirable to increase the beam energy, which can be expressed approximately as

$$E = 19n \sqrt{P_k} \times 10^6$$

where E is in electron volts, n is the number of klystrons sockets and P_k is the nominal value of klystron peak power output in megawatts. Budget limitations make it impossible to increase the number of klystron sockets, hence it is imperative to increase the peak power output of the klystrons to achieve higher energies. Considering power supply limitations and klystron life, a new objective peak power output of 34 MW, at a beam voltage of 270 kV was established. The end result should be a beam energy of approximately 25 GeV.

The improvement program undertaken to achieve this objective has resulted in klystrons producing 38 megawatts with 50% efficiency at 270 kV in permanent magnet, and 48 megawatts with 48% efficiency at 300 kV in electromagnet. A brief review of the Stanford klystron development, design and performance and computer analysis will be given. Life experience of all klystrons used at the accelerator center will also be reviewed.

2. Design and Performance

The Stanford klystron was designed initially to achieve reasonable efficiency (approximately 35%) with high gain (50 db) and extremely high rf output stability. Overall reliability for long tube life was also desired. Simplicity of design and beam focusing by permanent magnets were chosen as likely parameters in achieving those objectives. Fixed frequency operation allowed for a design with 5 non-tunable cavities. The beam microperveance is 2.00 ± 5% and 21 MW can be obtained at 250 kV with an efficiency of about 34%.[1,2] A cut-away view of the latest klystron and magnet is shown in Fig. 1.

Potential performance improvements by use of special harmonic cavities or extended interaction cavities were ruled out because of the likelihood of introducing instabilities in the output. Collector depression is impractical for pulsed tubes at these voltages. And the energy product of permanent magnet materials has not increased appreciably in the past few years to allow an increase of overall length at constant field without exceeding practical limits on diameter, weight and cost of the magnets.

Although the tube was initially designed with a gun intended for operation in Brillouin field,

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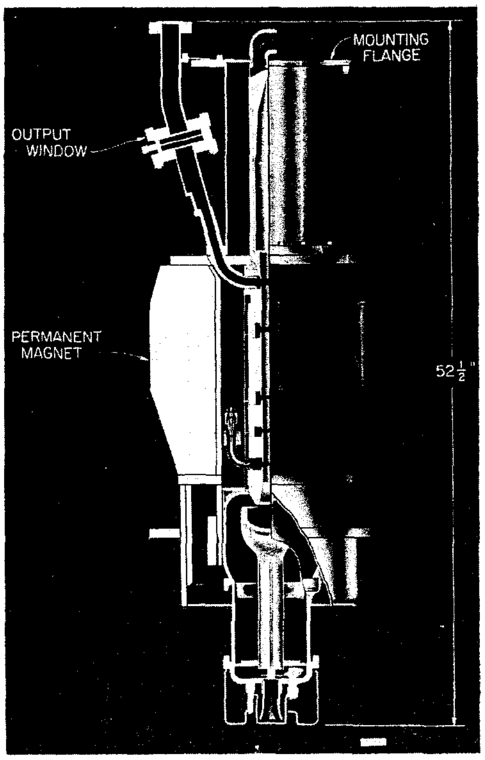

FIG. 1--SLAC klystron.

in practice the field in the third and fourth drift region was approximately twice the Brillouin design value. The gun operated satisfactorily in permanent magnets although the fringing fields extended in the cathode region. Accordingly it turns out that the calculations of drift distances are probably more accurate and give a better index for design evaluation by using confined flow focusing calculations than Brillouin focusing calculations. The analysis of the beam optics has been done by using Herrmannsfeldt's Poisson-solving gun program.[3] The magnetic field used in the Stanford klystron and adopted for the improvements discussed in this paper is shown in Fig. 2.

Within the above mentioned design limitations, we have followed a design philosophy closely following many of Mihran's ideas for optimum design.[4,5] However, a considerable portion of the work done at SLAC on klystron improvement has been of a more practical nature and many developmental models have been built since 1963. Figure 3 gives the performance obtained by the various developmental models. The values of drift length and output Qs chosen for the different models are given in Table I along with typical results under optimum focusing conditions. It can be seen that the trend in improvement has been to first optimize the output impedance and then adjust the drift distances based on calculations resulting from Mihran's initial work.

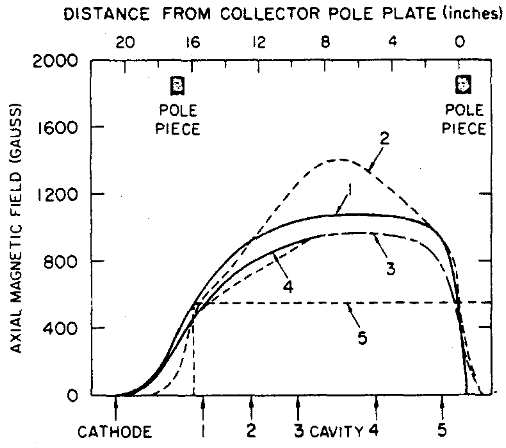

FIG. 2--Axial magnetic fields for Stanford klystrons
1-"standard" permanent magnet field
2-electromagnet field for XM-7 at 250 kV
3-electromagnet field for XM-12 at 250 kV
4-permanent magnet field for XM-12, 14b, 16a and 16c
5-540 gauss required for Brillouin flow.

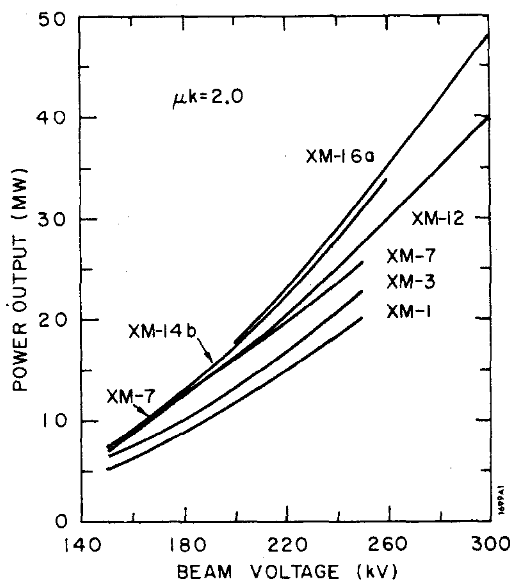

FIG. 3--Developmental model (XM-1 to XM-16a).

It appears that the efficiency continues to improve as the drift distance from third to fourth cavity is increasing. The longest model to date has a drift distance of L_{3-4} which is equal to 0.177 λ_g (for confined flow calculations) or 0.130 λ_g (for Brillouin flow). Theoretical considerations make us believe that longer drift distance L_{3-4} would further improve the efficiency but practical limitations discussed earlier have so far precluded serious consideration of longer drift distances.

The XM-16a can be considered as our present production model and shows a peak in efficiency of 49% at 260 kV in optimum focusing field. In general the efficiency drops by 3 to 4% when the tube is operated in permanent magnet. The results are shown in Fig. 4 which also includes data obtained

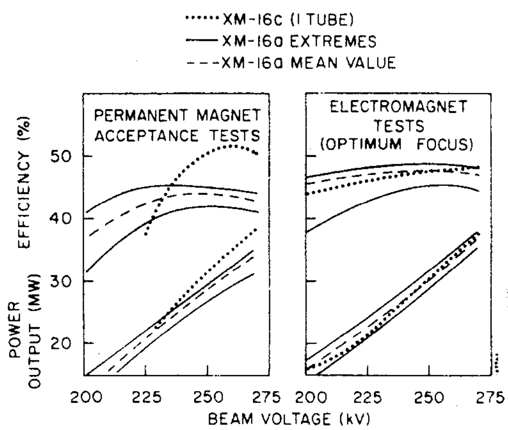

FIG. 4--XM-16a and XM-16c results.

with XM-16c, the latest development model tested. A XM-16c has demonstrated the highest efficiency to date and design parameters for that tube are given in Table II.

Frequency response curves are taken on all klystron designs and a 2% increase in efficiency has been seen in all models since the XM-7 when operating at approximately 10 MHz below the design frequency. Current designs are being built to establish the origin of this increase. The output cavity impedance and harmonic current/higher order cavity modes are being investigated.

In the process of this tube improvement program the feasibility of 300 kV operation was also considered seriously. Several tubes were built for this study, and Fig. 5 shows the results obtained.

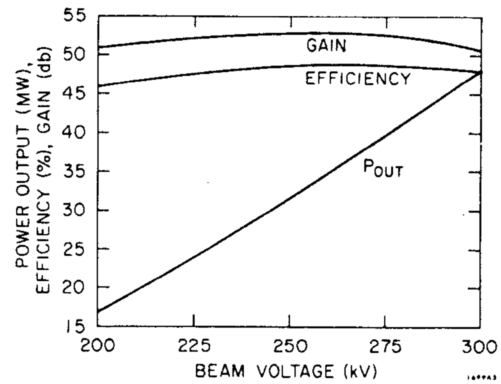

FIG. 5--XM-16a 300 kV tests.

A power output of 48 megawatts at an efficiency of 48% was achieved. However, this approach is only of theoretical interest because the major modifications needed to the modulators and the expected large reduction in the mean time to failure at this higher voltage operation makes it impractical for actual operation in the Stanford accelerator.

3. Windows

When power outputs in excess of 30 kilowatts average were first realized a number of windows appeared to become marginal in operation. A few failures by thermal shock were observed on SLAC built windows. It is believed that the failures were caused by an increase in the ambient temperature of the window which can cause a run away condition of the titanium coating on the alumina.[6] It was noted that the temperature gradient across the window had not increased significantly. Hence it was a reasonably simple matter to decrease the ambient temperature by water cooling the waveguides on either side of the window, which appears to have eliminated the thermal failures at 30 kilowatts. We have not attempted to cool the window sleeve directly since it would tend to increase the temperature gradient across the window and might make thermal failures more likely.

4. Computer Programs

It has been apparent for many years that computer programs could be developed to help in the design of high power klystrons under higher relativistic beam conditions. Such programs were not available to us but, with the cooperation of Lincoln Laboratories, Massachusetts Institute of Technology, an agreement was arrived at with Tore Wessel-Berg, Norwegian Institute of Technology, in Trondheim. With support divided between Lincoln Laboratories and SLAC, Wessel-Berg has developed a relativistic large signal klystron theory. The use of polarization variables makes this theory extremely well suited for computer usage. Successive iterations of nonlinear integral equations are taken to obtain large signal transmission matrices describing the nonlinear effects of various sections of the klystron. A computer program has been designed at SLAC using this theory for a basis and is currently being analyzed.

In the meantime Tallerico,[7] of Los Alamos Scientific Laboratory, had developed a large signal program which we have been able to adapt to our klystrons. In spite of the fact that some problems were encountered because of the relativistic effects in our tubes, relative improvements in efficiency can be predicted by utilizing the Tallerico program, as shown in Fig. 6 which reviews several of Stanford's designs.

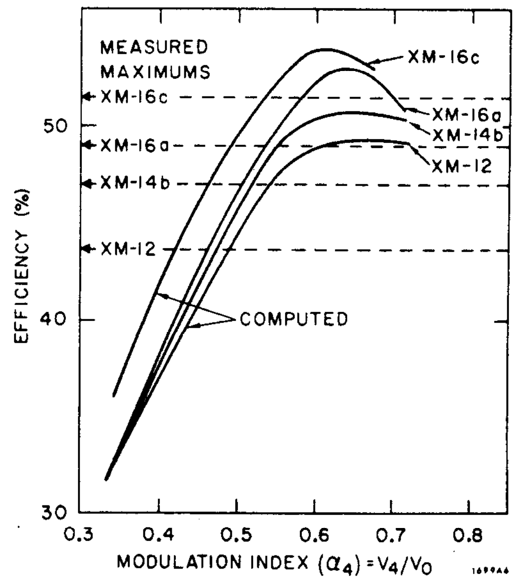

FIG. 6--Computer comparative results.

5. Operating Experience

As of the end of June 1970, 4,500,000 hours of klystron operation have been accumulated. There were a total of 289 failures distributed between the various vendors. The tube age distribution of both failed tubes and those operating on July 1, 1970, are given in Fig. 7. The failure and survival

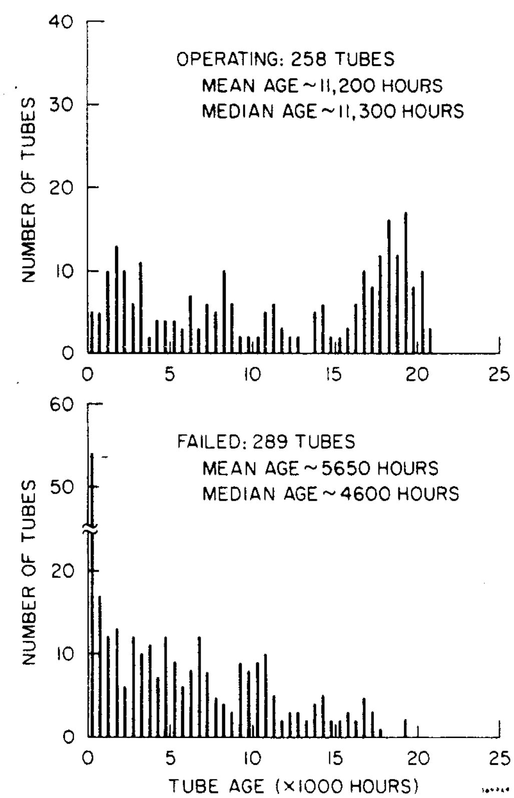

FIG 7--Tube age distribution (failed and operating).

probabilities for all tubes operated at SLAC have been computed from the above information and are plotted in Fig. 8. From this figure one can predict

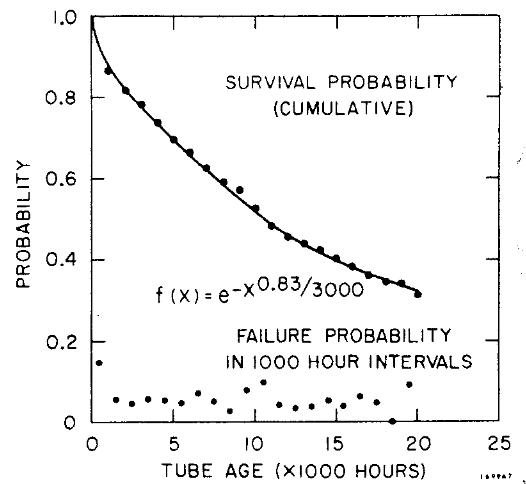

FIG. 8--Survival and failure probability.

a tube mean time between failures of 15,000 ± 3,000 hours.

Using Weibull analytical methods the probability survival distribution function was established to be

$$f(x) = e^{-x^{0.83}/3000}$$

and the mean time to failure

$$\mathrm{MTTF} = \int_0^\infty e^{-x^\beta/\alpha} = \Gamma(\beta^{-1})\,\alpha^{\beta^{-1}}/\beta = 15{,}000 \text{ hours},$$

where β is shape factor and α represents the scale factor.

Figure 9 shows the cumulative mean age at

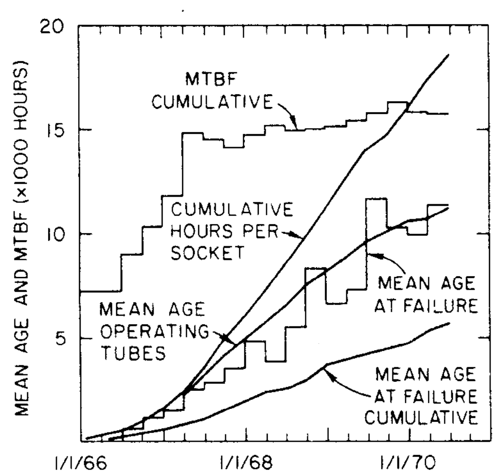

FIG. 9--MTBF and mean age at failure.

failure and the MTBF since the beginning of operation. MTBF is defined as ratio of cumulative klystron hours to the cumulative failures.

The fact that the failure probability shown in Fig. 8 is substantially constant and that the shape factor β of the Weibull distribution analysis is close to one indicates that no wear out mechanism has been observed up to now, even though 40% of the tubes now on the line have operated more than 16,000 hours each, and 25% more than 18,000 hours. The distribution of failure due to the various causes indicates that the majority of failures are window failures (40%). The next largest cause of failure is arcing (24%), followed by vacuum loss, gassiness and high voltage seal failures (22%). There were only 4% failures due to cathode or temperature limited operation and 10% for miscellaneous reasons such as oscillations, rf instabilities and mechanical problems. The failure mechanism distribution as a function of tube operating hours is given in Fig. 10.

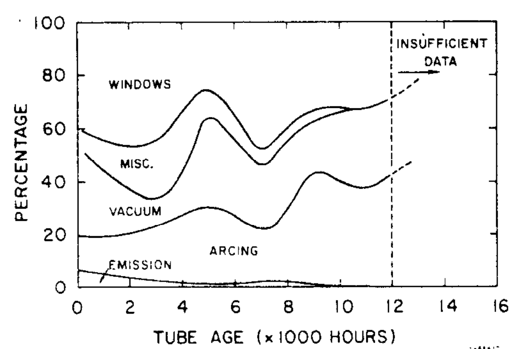

FIG. 10--Failure mechanisms (percent).

Very little experience has been obtained to date on klystrons operating at the 270 kV level. As mentioned previously there has been a tendency for additional window failures due to the higher average power. A slight increase in the rate of arcing failures has also been observed. The best present estimate is that the MTBF will be decreased between 20 and 30% from the value obtained at 250 kV.

6. Conclusions

Stanford and its vendors have developed klystrons capable of achieving the highest peak rf power outputs obtained while maintaining an extremely reliable design. The Linear Accelerator Center produces approximately 20% of the tubes used on the accelerator and has attempted to maintain the state of the art in the super power area to give both an efficient and reliable design. It is felt that our development programs have been extremely rewarding in the general improvement of not only our own tubes but also those of our vendors.

It is hoped that the computer programs being used at present will become useful tools in future development of Stanford's klystron and that greater knowledge of klystrons operating at highly relativistic beams can be obtained.

After careful review of various design models it appears that efficiency can be increased beyond our present results, and that power outputs of 43 MW and 54 MW at 270 kV and 300 kV respectively in the permanent magnet are possible.

32 sockets of the accelerator have already been equipped with klystrons operating at 270 kV. As a result, the maximum accelerator beam energy measured is now 22.1 GeV, an increase of approximately 2.5% over the previous high.

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TABLE I

Drift Lengths (cm)	XM-1	XM-3	XM-7	XM-12	XM-14b	XM-16a	XM-16c
L_{1-2}	7.62	7.35	7.35	7.34	7.34	6.83	6.19
L_{2-3}	7.62	7.26	7.26	7.26	7.26	6.75	6.12
L_{3-4}	8.89	12.30	11.86	11.89	12.25	13.69	17.75
L_{4-5}	8.89	9.46	10.16	10.13	9.49	9.49	9.49
Output Q	27	21	21	20	19	19	19
Efficiency (%)	32.5	37.0	41.5	43.5	46.6	48.6	51.5
Year	1963	1963	1964	1966	1967	1968	1970

In tubes XM-1 to XM-7 the drift tube radius was 1.43 cm. For all tubes XM-12 and subsequent the first and second drift tube radius were 1.43 and the third and fourth were 1.54 cm.

TABLE II

XM-16c DESIGN PARAMETERS

Cavity Gap (cm)	R/Q	Q	Freq MHz	Drift Length
.51	80	400	2856	6.19
.51	62	~4000	2857	6.12
.64	87	~5000	2860	17.75
.89	82	~5000	2916	9.49
1.16	96	19	2856	

Normalized drift tube radius $(\gamma a)_{1-2} = 0.8$, $(\gamma a)_{3-4} = 0.9$

Normalized beam radius $(\gamma b) = 0.6$

Reduced plasma wave length (λ_q) = 102 cm (confined flow)