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STATUS REPORT ON KLYSTRON IMPROVEMENTS*

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Introduction

One of the main functions of the Klystron Group at SLAC is to prosecute a program of improvements of the high power pulsed klystrons used in the gallery, originally designed to operate at 250 kV with a peak power output of between 21 and 24 MW.[1] The initial upgrading of the klystron power was achieved by a minor improvement in efficiency but a substantial change in operating conditions; the beam voltage was raised from 250 to 270 kV beginning in 1970.[2]

As of now one-third of the machine (80 stations) is equipped with klystrons operating at between 265 and 270 kV with peak power outputs of between 28 and 30 MW at the operating level. All these klystrons are focused by permanent magnets.

Approximately three years ago when looking for further improvements in efficiency two approaches appeared theoretically feasible. One was the introduction of second harmonic cavities in the beam to improve the bunching at the output gap. The other was to take advantage of space charge forces to achieve the same result by increasing drift length and adding a detuned cavity. These approaches have been suggested in the literature by Lien, of Varian,[3] and Mihran, of G. E.[4]

It was not felt possible to use the second harmonic cavities in the SLAC design because the drift tube diameter is almost equal to the pillbox diameter for second harmonic frequency; hence it was decided to attempt to increase efficiency by increasing interaction length. Initial results have been reported previously by Stringall.[5]

As a result of the excellent test data obtained on the long interaction klystron it was decided to embark upon a program to build such tubes at SLAC and to procure electromagnets for installation in the gallery.

This paper will review the design of the new high efficiency klystron, the special requirements for electromagnets and interlocks for focusing the tubes, as well as the performance of the first two sectors, which have now been in operation for approximately six months.

The remainder of the paper will be devoted to a review of the operating life experience of all high power pulsed klystrons used at Stanford.

Design

The basic design changes between our standard 30 MW klystrons and our present 40 MWs have been established by the use of a computer program described previously.[5] The improved bunching needed to enhance the efficiency of the klystrons can be achieved by the addition of a prepenultimate cavity which is detuned by almost the same amount as the penultimate cavity. Hence, not only does the overall interaction length of the klystron increase from about 40 cm to 67 cm, but the number of cavities is increased from 5 to 6 to maintain adequate gain. Data obtained on the test vehicles indicated that all cavities needed to be detuned on the high side of the drive frequency to achieve maximum efficiency with the drift distances selected from the computer program. In practice then the tube consists of a high gain section (cavities 1 and 2). The third cavity is detuned by slightly more than f_o/Q to the high side and the prepenultimate and the penultimate cavities are detuned by at least 4 f_o/Q of the drive frequency.

The following table gives the actual values of cavity frequencies used in the experimental tube as well as the drift distances expressed in reduced plasma wavelength (λ_q). For comparison, typical values of frequencies and drift length of our 30 MW permanent magnet-focused klystrons are also given in the table.

Cavity No.	PM FOCUSED 30 MW Tubes Frequency (MHz)	PM FOCUSED 30 MW Tubes Drift Length (λ_q)	EM FOCUSED 40 MW Tubes Frequency (MHz)	EM FOCUSED 40 MW Tubes Drift Length (λ_q)
1	2856		2859	
		.06		.06
2	2857		2865	
		.06		.06
3	2860		2874	
		.174		.284
4	2916		2922	
		.093		.16
5	2856		2927	
				.093
6			2857	

The differences between the standard SLAC tube and the new high efficiency tube are illustrated in Fig. 1. Fig. 1(a) is an outline drawing of the standard, permanent magnet-focused, tube; 1(b) is the outline drawing of the electromagnet-focused 40 MW tube, with both figures being at the same scale. It can be seen that the cathodes are identical; the input sections are the same; the output system and the collectors are identical.

Focusing

A tube built to the values of the table above and operating in a carefully adjusted focusing field controlled by nine individual supplies achieved the efficiencies and power outputs reported previously.[5]

Because of the additional length of the tube and the criticalness of the focusing field it was deemed impossible to achieve this performance by the use of permanent magnets. The permanent magnets presently in use at SLAC for the 30 MW klystrons have an active magnetic field length of about 18 inches. To increase that length without the use of field reversal would increase both the cost and the weight of the magnets to totally impractical values. Hence the 40 MW tubes, which have been built since, are being focused by electromagnets which could be controlled from a single current-regulated supply. The magnets were specified to provide some flexibility of field shape by trim coils along the length to optimize the field shape within limits in case of different performances from tube to tube. They are water-cooled, and power consumption for focusing is between $1\frac{1}{2}$ and 2 kW per unit. The water cooling for the magnets is designed to take the full water flow of the klystron in order to reduce the complexity of the interlock system.

As of now we have two sectors equipped with electromagnet-focused klystrons of the design outlined above.

Interlocks

As seen in Fig. 1, the Stanford klystrons are not built with insulated collectors. Hence the standard procedure of

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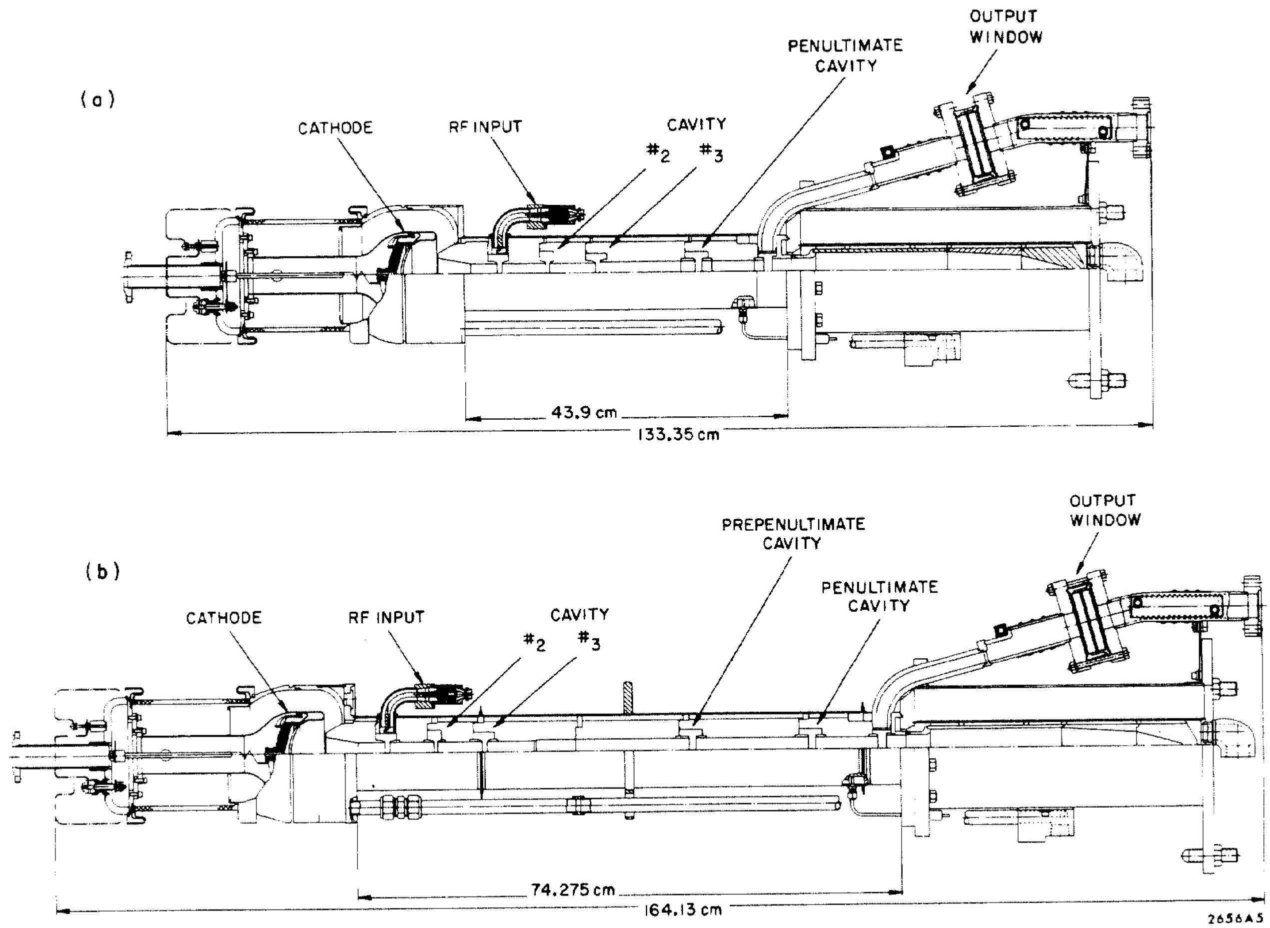

FIG. 1--SLAC klystron outline drawing. (a) Standard (30 MW) permanent magnet-focused magnet. (b) 40 MW electromagnet-focused tube.

metering body current and using excess body current as protection to the tube cannot be used in this case. Instead we have designed a water temperature interlock by which the differences in temperature between the output and input cavity can be measured accurately. By use of platinum resistance thermometers it is possible to measure accurately variation in the temperature differences of as little as 0.1° C. Since at the water flow used the total klystron beam power responds to a temperature rise of approximately 30° C, it is thus possible to control the beam interception to change less than 1 percent of the total beam power.

In addition, we have had a circuit designed for us by Accelerator Electronics by which power output changes of a few percent from pulse to pulse can be recognized. Experience has indicated that random changes in power output from pulse to pulse are almost always an indication of poor focusing and particularly excessive interception on the output nose next to the collector. This is one kind of interception which cannot be detected readily by the water Δ_T described above. With this additional protection circuit we feel that the possible damage to the tube body due to slow variations in magnetic field caused by focusing current changes will not result in damage to the klystron.

In addition there are the usual limits on focusing current and voltage, particularly on the field shaping coil in the cathode region, which has been designed to operate with slightly less current than the remainder of the magnet.

Performance

As a result of the focusing compromises needed to make the experimental tubes practical, and the fact that all cavities are not tuned for optimum output during initial tests, the power output achieved on the experimental tube has not been duplicated exactly in production. The first 25 electromagnet-focused tubes accepted for operation in the machine have, on the average, a peak power output of 37.9 MW (measured calorimetrically) at 270 kV, resulting in a beam efficiency of 48.8 percent.

For comparison, a similar number of standard 30 MW klystrons built during the same period achieved a peak power output of 30.3 MW at 270 kV on the average with an efficiency of 39.0 percent.

Based on the latest measurement of energy contribution of 20.191 $\mathrm{MeV}/\sqrt{\mathrm{MW}}$, SLAC stations equipped with our electromagnet-focused tubes would contribute a no-load energy of 124 MeV per station. Hence, the final energy for the accelerator could be raised to 29.8 GeV with a full complement of these tubes.

Operating Experience

One of the important factors in operation of a high energy accelerator is obviously the cost; in the case of SLAC the klystron replacement cost was thought to be potentially one of the highest operating costs of the machine. Fortunately the experience over the past nine years has indicated that the mean time between failures of all tubes used at SLAC is almost 17,000 hours and still climbing (see Fig. 2).

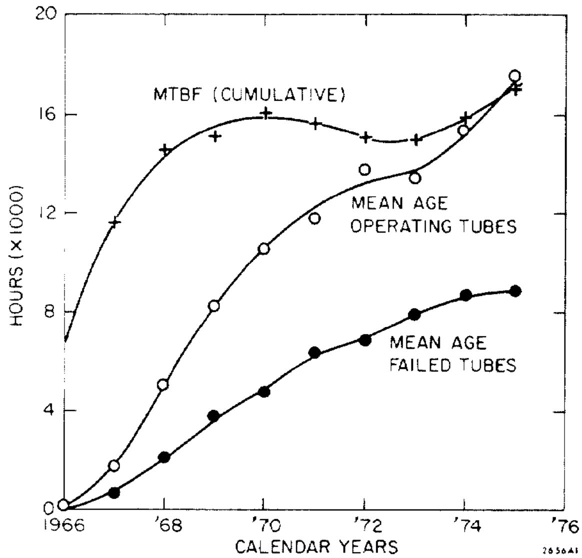

FIG. 2--Operating statistics SLAC high power klystrons.

The other plots on Fig. 2 indicate that the mean age of all tubes operating on the accelerator is approaching 17,500 hours, but the mean age of all failed tubes is only 8,800 hours. Figures 3 and 4 give the age distribution of all operating tubes and of all tubes which have failed at SLAC since

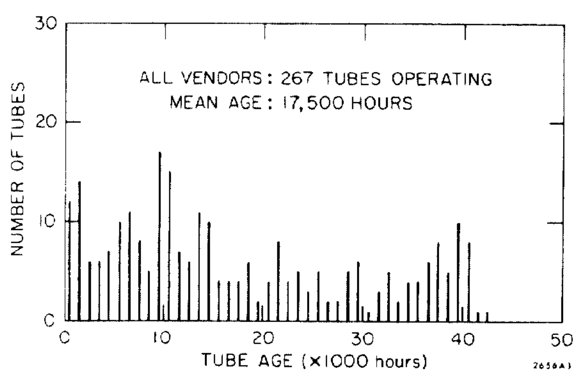

FIG. 3--Age distribution all operating klystrons at SLAC.

1966. The data of these two figures have been analyzed to determine the failure probability per thousand hours of operation, and the survival probability of all tubes. Those results are plotted in Fig. 5.

From Fig. 5 it is seen that the failure probability is substantially constant at slightly less than 5 percent per thousand hours through a lifetime of at least 35,000 hours for the tube (we have had no tube failures yet for tubes with more than 35,000 hours of operation). If the failure rate were exactly constant we would then have a completely random failure mechanism and an exponential survival probability. Again, under this assumption the predicted mean time between failures would be 20,000 hours.

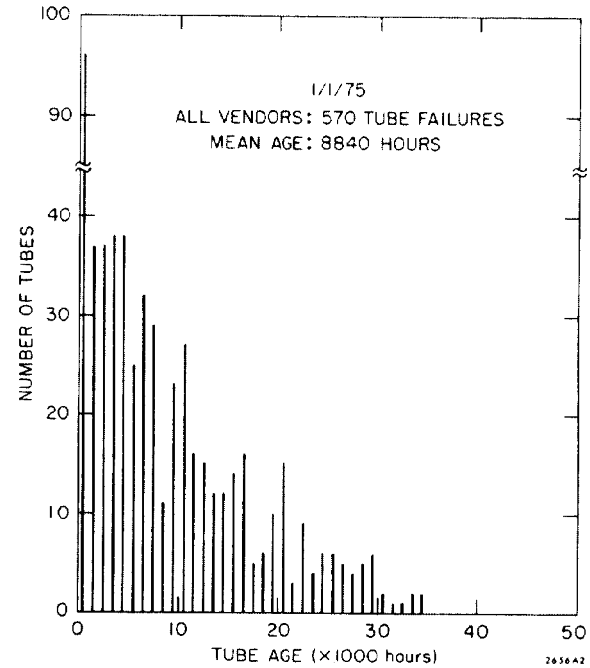

FIG. 4--Age distribution all high power klystrons failed at SLAC.

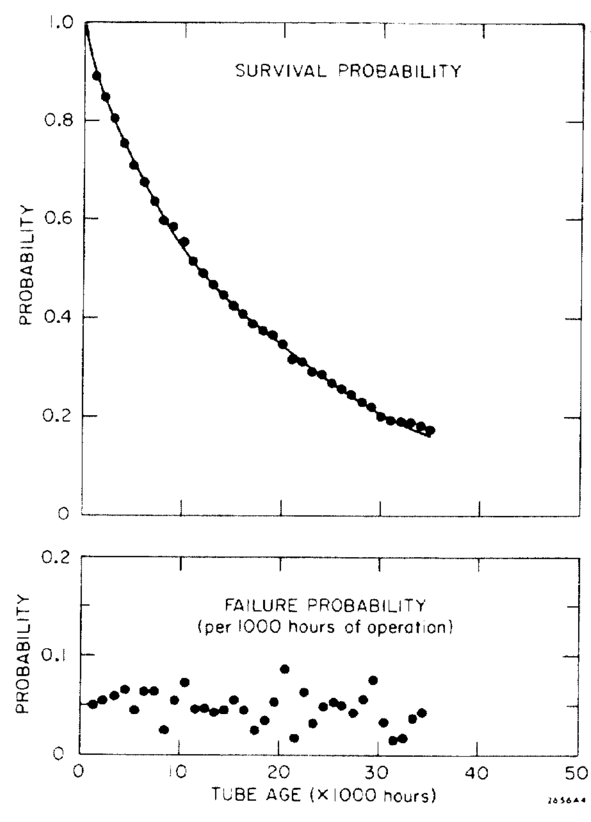

FIG. 5--SLAC high power klystrons failure analysis all tubes. Sample = 837 tubes.

It is obviously not possible to say that all tubes installed at all times since the beginning of operation have had this type of performance. For instance, some tubes delivered between 1968 and 1969 have a relatively low failure age.

For some reason tubes of a given vendor at that time suffered from temperature-limited cathode (lack of emission) at a mean age of 7,000 ± 2,000 hours. We also find some tubes built at SLAC which appear to become temperature-limited at 15,000 ± 2,000 hours.

The surprising thing is that there are no major fluctuations in the failure rate experienced in the klystron operation at SLAC in spite of upgrading 10 sectors of the accelerator from 245 to 265 kV in July 1972, and in spite of the change of 2 sectors to operate at 265 kV, 38 MW klystrons since September 1974.

In fact we have analyzed on very limited data the failure of tubes which have operated at 265 kV (30 MW) since their installation. This analysis indicates that the MTBF for these tubes should be substantially equal to the overall average obtained since 1966. The total statistical analysis of failure of klystrons operating at SLAC is also complicated by the fact that the operating conditions are not always fixed. Lately we have been operating at reduced repetition rate in order to conserve energy but no significant data have been obtained to indicate a direct correlation between repetition rate and tube life.

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