10

KLYSTRONS

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The klystrons used on the Stanford two-mile accelerator were developed specifically to operate in permanent magnets with reasonable efficiency, as well as to achieve long life and minimum operating costs. The feasibility of permanent magnet focusing at peak powers in excess of 20 MW was demonstrated by development programs undertaken at SLAC and in industry. Extensive window development work undoubtedly contributed to the achievement of long life and reliability of the tubes now in use. The operating experience to date has been very good, with a predicted mean time to failure in excess of 8000 hours.

10-1 Selection of RF sources (JVL)

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 successful in demonstrating 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 accurately phasing a large number of oscillators. In addition, it was felt that the rather short life expectancy and the relatively low peak power of magnetrons would make this type of tube unsuitable for use in a large accelerator.

The amplitron has the advantages of high 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 amplifier chains and high-power isolators. In addition, amplitrons can oscillate in spurious modes unless the drive power is applied for a longer time than the cathode power. In case of drive failure, the resulting oscillations can produce failures of both the input and output windows.

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 easily be 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 15 years and in many radar applications indicates the potentially long life of this device.

However, the amplitron appeared sufficiently promising to warrant an extensive study of its possible applications. The results of that study[2] indicated that, although there would be a slight reduction in power costs, the disadvantages of the amplitron system made its adoption inadvisable for the SLAC accelerator. The main reasons are outlined below:

1. From a general system standpoint, it is essential to evacuate the waveguide between the RF source and the accelerator. Amplitrons at that time (1961) were known to be susceptible to failures of both the input and output windows. Consequently, it would have been necessary to evacuate not only the output waveguides but also the drive line to the amplitron to prevent losing the vacuum in the accelerator in case of double window failure.
2. Although the amplitron by itself has a very good phase stability, the low gain requires the use of a waveguide drive line and additional amplifiers in series. Unless the waveguide temperature is controlled to better than $\pm 1\,^{\circ}C$, the resulting overall phase stability is inferior to that of the klystron system.
3. The possible effects of amplitron oscillations or spurious signals on the behavior of the accelerated beam are not well understood and made the consequences of adopting this RF source uncertain.
4. The added complexity of the amplitron system as visualized for the Stanford accelerator and the attendant increase in initial installation cost would not be offset by reduced power cost resulting from high amplitron efficiency.

The above comments are not meant to imply that amplitrons should not be considered in other linear accelerators where the design requirements (e.g., high duty cycle or small number of RF sources) might favor adoption of this tube.

Another factor influencing this decision was the well-advanced stage of development of high-power klystrons. In 1944, E. L. Ginzton suggested that it would be possible to build klystron amplifiers each delivering 15–30 MW of pulsed power at S-band. 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.[3] The same basic design is still used in some of the sockets of the Mark III accelerator at Stanford, and considerable development work was carried on at Stanford.[4] 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, and at EMI and AEI in England. In this country, tubes were produced capable of 3-MW peak power and 50-kW average power at C-band, 20-MW peak and 54-kW average power at L-band, and 10-MW peak and 20-kW average power at S-band. The French development work resulted in tubes capable of 20- to 30-MW peak power at S-band, with average power capabilities in excess of 20 kW.

One of the major considerations in the design of all systems for the accelerator including the RF sources was the desire to obtain maximum reliability. In addition, the potential operating costs were also carefully considered. It was felt that the reliability of the klystron system would be much greater than that of an amplitron system since the total number of components in the former system is much lower. From a standpoint of accelerator operating expense, one of the major factors is tube replacement cost. Although meaningful operating experience at peak power outputs of $\approx$20 MW was not available for either amplitrons or klystrons, it was felt that, based on radar system experience, the life of a conservatively designed klystron would probably be greater than the life of the amplitron. In addition, it was known that klystron tubes can be repaired many times, thus reducing the average cost per hour below that obtained if only new tubes could be used.

For all the reasons mentioned above, it was decided to use klystrons to provide the RF power for the Stanford linear accelerator.

10-2 Specifications (JVL)

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, to achieve the desired narrow beam energy spectrum from the Stanford two-mile accelerator it was necessary to limit the maximum phase deviation at any of the 960 feed points of the machine to $\approx 5°$. 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 stable sources, the drive lines, the preamplifier (booster and sub-booster) klystrons, the final amplifier klystrons, and the waveguide system to the accelerator. Thus, along with other stringent systems requirements, extremely tight specifications had to be imposed on the phase modulation within the final klystron amplifier. Furthermore, amplitude modulation on the RF output pulse would also result in spectrum broadening, and the maximum allowable amplitude modulation had to be limited.

Although the simplified theory indicates complete isolation between the amplifier stages in a klystron, in practice some oscillation or feedback mechanisms are possible, due either to reflected electrons or to a tendency for cavities to oscillate at frequencies above the driving frequency. Moreover, 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 normal practices. For example, a careful study of the focusing problems indicated that there was a potential saving to be obtained from eliminating electromagnets and their power supplies with their attendant water cooling and interlock requirements. Hence, it was decided to design the tube in such a way that it could be focussed by permanent magnets. Following the Stanford Mark III practice, it was also deemed desirable to evacuate the waveguide runs between the klystron and the accelerator.

Another deviation concerns the method of mounting the tube. Because of slow lateral movements of the long accelerator housing and the necessity of accurate accelerator alignment, it is expected that it may be necessary to move the feed points gradually with respect to the housing by as much as 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 the klystron and pulse transformer tank from the frame to minimize the tolerance problems in making the klystron-to-waveguide vacuum joint. This method has the additional advantage of allowing variations in overall klystron length without having to change the mechanical installation system. Hence, there is flexibility for continuing improvements in the klystron design.

The cooling requirements of the tube are met by use of low-conductivity deionized water. To simplify the water and interlock systems, it was decided that the tube body and collector would be cooled in series, and that the available flow and pressure drop would be 10 gal/min and 30 psi, respectively.

Table 10-1 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.

10-3 Procurements (JVL)

Because it was decided that the SLAC tube should be focused by a permanent magnet and no such tubes existed at SLAC power levels, it was obviously necessary to instigate an extensive development program. The majority of the tubes used to power the accelerator were to be procured from industry, and it appeared essential to have two sources of supply for such tubes to insure a continuing supply in the event of delays from one vendor. To achieve the lowest possible operating costs, it was decided to follow the experience of the Mark III accelerator and use tubes which could easily be repaired and rebuilt after failure.

Consequently, the development effort had a double objective. The first was to demonstrate that the peak and average powers required for the SLAC accelerator could be obtained with permanent-magnet-focused klystrons. The

Table 10-1 Comparison of Mark III and SLAC klystron specifications

Parameter	*Unit*	*Mark III accelerator klystron*	*SLAC klystron*
Operating frequency	MHz	2856	2856
RF pulse width	μsec	2	2.5
Repetition rate	pulses/sec	60	60–360
Peak power output	MW	20	24[a]
Heater power	W	600	270
Beam voltage	kV	325	250
Beam current	A	185	250
Microperveance	10^{-6} A/$V^{3/2}$	1	2
Peak drive power	kW	10	0.24
Gain	dB	33	50
Amplitude modulation	%		1 (max)
Phase modulation, maximum	deg		1 (heater hum) 8 (for 1 % beam voltage varia 1 (any other cause)
Noise power (with respect to fundamental power)			<−40dB in any 1 MHz band ı 5000 MHz <−25dB in any 1 MHz band 5000 MHz
Focusing		Electromagnet	Permanent magnet
Radiation	mR/hour		3 maximum at 3 ft
Faults			Less than 10 in 8 consecutive ho

[a] Acceptance specifications: 21 MW at 250 kV, 12 MW at 200 kV.

second was to achieve an economical design of an easily repairable tube that could be readily transferred to manufacturing.

Accordingly, the development effort was divided among Stanford and two tube manufacturers, RCA and Sperry. It was hoped that at the end of a development period of approximately 1 yr, SLAC could procure tubes at a minimum cost on the basis of performance specifications after supplying the detailed designs resulting from the development programs to the various tube manufacturing companies. Unfortunately, at the end of the development program a full specification tube had not been achieved, but sufficient knowledge had been acquired to dispel any doubts about the feasibility of meeting the specification with a permanent-magnet-focused klystron.

During the initial phases of procurement of production tubes, both vendors (RCA and Sperry) encountered difficulties which resulted in delays in deliveries, and Stanford procured a few experimental tubes from two additional companies, Eimac and Litton. In order to meet construction schedules, it was necessary to increase the klystron delivery rate by having a third industrial supplier (Litton). Hence, there are now on the machine tubes from three production suppliers (RCA, Litton, and Sperry) as well as SLAC-built tubes.

10-4 Design considerations and development work (JVL)

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

The electron gun

Stanford's klystron initially used a gun designed by J. Picquendar of CFTH.[5,6] This gun, designed as a magnetic field-free (magnetically shielded) 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.[7] As a result, G. K. Merdinian designed a gun specifically for use with the Stanford klystron.

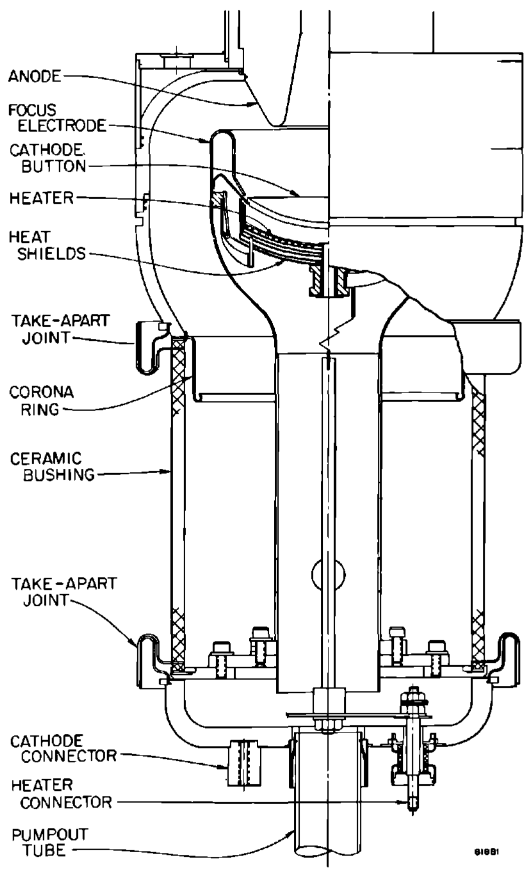
This new gun (Merdinian gun) was designed following Pierce's theory,[8] with the introduction of an additional correction factor to compensate for the presence of a large anode hole. The design of electrode shapes was carried out in an electrolytic tank, after which the gun was analyzed on an IBM 7090 computer, where Laplace and Poisson's equations were solved simultaneously. The electrostatically focused, minimum beam diameter is approximately 0.9 in. After the beam passes through the magnetic pole plate, the beam diameter converges to approximately 0.8 in. It was also found experimentally that this gun operates extremely well under partially confined flow conditions, and that the permanent magnets which have been procured exhibit the proper field shape in the gun region to satisfy these conditions. For this type of operation, it is believed that the beam diameter is still approximately 0.8 in. For Brillouin flow,[9] the magnetic field required to focus the beam is approximately 600 G. In practice, because of the density bunching near the output cavities, the field needs to be increased to approximately 1000 G. The same field should also be adequate for focusing the beam under partially confined flow conditions.

With this design, gun oscillations have been virtually nonexistent. It is believed that in most high-voltage and high-perveance guns, Llewellyn-type diode oscillations[10] are prevalent. Because these oscillations take place between the cathode and anode noses in a cavity formed between the cathode support and the anode housing, loading of this cavity tends to decrease or suppress the oscillations. A smooth transition between the high-voltage bushing and anode nose is intended to provide loading by the pulse transformer tank oil. In the early work with permanent magnets, the anode housing had been lengthened, and under these conditions oscillations were detected in the gun region.

It has also proven easier to design permanent magnets to provide a small threading field at the cathode rather than to obtain a true zero-field condition as required by the Brillouin gun theory. A combination of the Merdinian gun and the experimental magnets which were procured gave, in general, much better results than the combination of the Picquendar gun and the experimental magnets. For these various reasons, the SLAC-built tubes during the past several years have utilized the Merdinian gun. The only further improvement made on that gun consisted of minor modifications in the cathode button radius of curvature to compensate for thermal expansion and of mechanical changes in heat-shielding arrangements and heater position.

The present layout of the gun is shown schematically in Fig. 10-1. The cathode button diameter is approximately 7.94 cm and the spherical radius 6.9 cm, giving a solid angle of 35°. The total cathode emitting area is approximately 54 cm^2 resulting in a very conservative cathode loading of less than

Figure 10-1 Stanford electron gun layout.



5 A/cm^2. The area convergence ratio of the gun is approximately 16 (depending on the actual beam diameter achieved).

Like Stanford, RCA started their development program by using Picquendar's gun. Unlike Stanford, RCA has found practically no oscillation problems with this 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 a gun of their own design which operates in a field-free region 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 wavelength slots in the focus electrodes, and loading in the anode housing.

Eimac initially was planning to use a gun which had been designed specifically for operation under fully confined flow conditions. The advantage of a confined flow gun is the potential improvement in efficiency. Unfortunately, strong 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 strong gun oscillations. The cause of these oscillations was traced to a change in 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.

The interaction space

With the beam diameter given at 0.8 in., a drift tube diameter of $1\frac{1}{8}$ in. was chosen as a compromise between optimum coupling and minimum 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 MHz or a reduced plasma wavelength of 55 in. The normalized drift tube and beam radii are $\gamma_a = 0.775$ and $\gamma_b = 0.551$ rad, respectively.[11] Theoretical design based on Webber's model[12] indicates that optimum gain and efficiency should be achieved for a total interaction length between 20 and 24 in. However, it appeared certain that a reasonably uniform magnetic field of between 800 and 1000 G could not be achieved over an interaction length of 20 in. by permanent magnets. Hence, since gain and efficiency near the optimum do not vary rapidly with length, the first tubes built at SLAC were designed with a total interaction length of approximately 17 in., as a compromise between magnet design and electrical tube design requirements.

These tubes operated with electromagnetic focusing at an efficiency of approximately 35% in the voltage range between 200 and 250 kV. The measured field requirements were approximately as expected, but discussions with permanent magnet manufacturers indicated that it would not be feasible to achieve the required fields over a length of 18 to 20 in. without unacceptable increases in size, weight, and cost. Accordingly, a further reduction in tube length was decided upon and the interaction space was designed to fit within a total magnet length of approximately 16½ in. The first tubes built to this new length were still using the Picquendar gun and gave rather disappointing results: the efficiency rarely exceeded 32%, and the power output never exceeded 19 MW. Using the same body with the Merdinian gun, the output and efficiency both improved, but were still disappointing. A series of modifications were then undertaken to bring the performance up to desired levels.

The coupling coefficients were computed as being approximately 0.383 for the buncher cavities and 0.707 for the output cavities (although the cavity gap lengths and gap diameters were approximately the same, the relativistic computation resulted in the large difference in coupling coefficients). Table 10-2 gives the successive modifications introduced in the interaction dimensions. The overall drift distance increase was achieved without modification in permanent magnet length by reducing the distance between the pole plates and cavities to the minimum compatible with stable operation. The maximum possible reduction was determined mostly experimentally.

The change in output Q was first determined by recomputation and was then confirmed experimentally. Normal variation in power output from tube to tube makes it difficult to optimize the output coupling unless a large sample of tubes is used.

The potential problems of oscillations in the tube body were recognized when the design was started, although not fully appreciated. The initial design included cavities with different aspect ratios (height-to-diameter ratios). In this way, the frequencies of the second and third resonant modes are different from cavity to cavity, and there is little possibility of producing oscillations by drift tube coupling at these higher mode frequencies. In spite of these precautions, some tubes exhibited higher mode oscillations. Analysis showed that these oscillations were probably of a monotron type, caused by a TM_{12} mode which is strongest with symmetrical cavities. A redesign of the cavities with opposing noses of different length has apparently solved that oscillation problem. Some oscillations which produced an amplitude ripple on the RF output pulse were also observed. These apparently result from feedback between the first stages of the tube and were observed only on two tubes

Table 10-2 Drift distances

Drift distance	*XM-1 (in.)*	*XM-2 (in.)*	*XM-3 (in.)*	*XM-7 (in.)*	*XM-12 (in.)*
L_{1-2}	3.0	2.875	2.894	2.894	2.894
L_{2-3}	3.0	3.000	2.857	2.857	2.857
L_{3-4}	3.5	4.250	4.842	4.568	4.568
L_{4-5}	3.5	3.750	3.726	4.000	4.000
Total	13.0	13.857	14.319	14.319	14.319
Q_e Output	25–30	20–25	18–20	18–20	18–20

where the cavities were tuned to the same frequency—a frequency which was different from the drive frequency. Because of the overall length limitation, the drift distances in the voltage amplifier portion of the klystron are very small and the cavities are not completely decoupled from one another. Thus it is possible to have, in effect, a two-cavity oscillator, the output of which combines with the drive frequency to give a beat at the frequency of the amplitude ripple observed on the RF output.

Under certain conditions, one can also observe oscillation caused by returning electrons. Whether these originate from the output gap or from secondaries emitted in the collector region is not clear. However, it is known that the magnetic field through the collector region will tend to focus secondaries back into the drift section. With permanent magnet focusing as used in SLAC tubes, there is an appreciable magnetic field at the collector.

The vendors have also experienced the same kind of oscillations observed in SLAC tubes. In general, the sources have been the same and similar corrective steps have been taken. In addition, cavity oscillations have been suppressed by introducing losses either by plating the whole cavity with lossy material (Litton technique) or by introducing a frequency selective loss by means of pins or loops in the cavity (RCA technique).

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 considered optimum for the usual electromagnetic focusing. As observed above, focusing of secondary electrons by this stray field may also cause unwanted reactions with the main beam in the output section of the klystron.

Collector oscillations can exist because of the propagation of waves in the collector and drift tubes at frequencies above the cutoff frequencies corresponding to their diameters. As a result, there can be regeneration in the cavity oscillation mode described previously. However, it was found possible to change the phase of the reflected waves to the cavity by adjusting collector length and, thus, to eliminate the oscillations.

Although SLAC 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.

The SLAC collector is approximately 4 cm in diameter and 37 cm long, giving a total area of approximately 470 cm^2 exposed to the beam. When the tube is operating without drive and without focusing, the average power density over the collector would be approximately 170 W/cm^2 at full beam voltage. With electromagnetic focusing, the maximum power density is computed as approximately 1 kW/cm^2 at no drive. Although accurate calculations have not been made for the maximum power density with permanent magnet focusing, it is believed to be approximately 0.7 kW/cm^2 and, hence, quite conservative.

From a mechanical standpoint, the SLAC collector is an integral part of the tube and cooling is obtained by flowing water through a spiral groove on the outside of the collector with a very high Reynolds number to achieve efficient heat transfer.

In general, there have been few problems with the collector design, although some tubes have shown erosion caused either by beam focusing near the tip of the collector or by a skewed beam probably due to transverse fields.

The permanent magnet

The magnets used to focus the SLAC klystron are barrel shaped and are designed for a gap length of $16\frac{1}{2}$ in. with an inside diameter of approximately $8\frac{1}{2}$ in., providing space for insertion of lead shielding and for easy removal of the tube from the magnet. The maximum outside diameter is approximately 18 in., and the total weight is nearly 800 lb. The magnetic material used is Alnico 8.

The typical reversal of the magnetic field on both ends 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 by 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 problems remaining with permanent magnets is that of cross or transverse magnetic field. The transverse fields can be reduced either by very careful magnetizing or by using magnetic shunts. These shunts consist of either thin magnetic plates normal to the main field axis or thin steel cylinders coaxial with 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, SLAC has built a magnetizer to bring magnets back to full specifications if they are accidentally weakened below the useful range of magnetic fields.

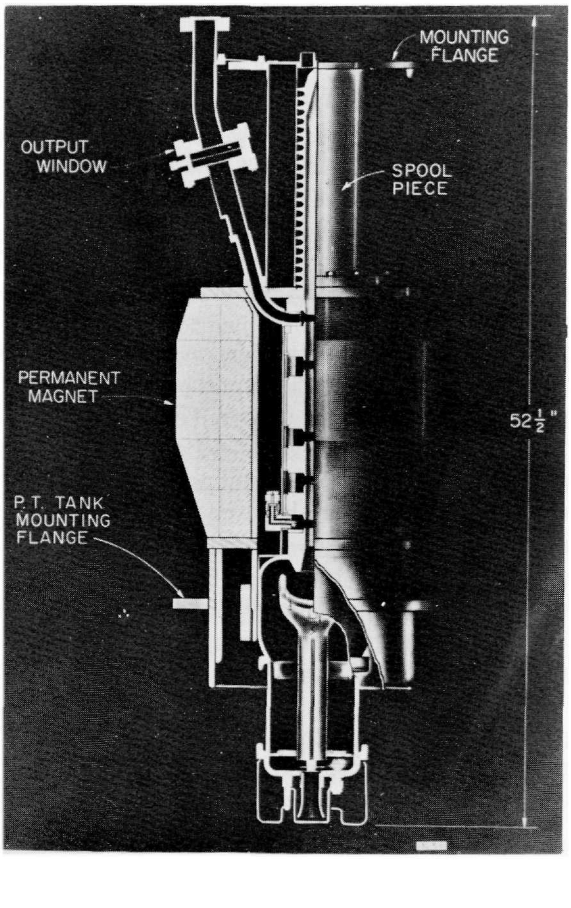
RCA is procuring magnets to specifications that carefully limit the maximum amplitude of transverse fields as well as the range of acceptable magnetic fields. Sperry uses magnets that match the requirements for a Brillouin focused beam.

10-5 Klystron mechanical design (JVL)

As mentioned earlier, the SLAC klystron is designed so that a vacuum seal can be made to the waveguide system in spite of the possible variation in height and location of the waveguide feed of several inches with respect to the floor of the klystron gallery. To achieve this result, the klystron is suspended from a yoke to which the waveguide is attached. The whole yoke is mounted on an I-beam frame which is adjustable in height and position.

The klystron output waveguide flange is accurately located with respect to three mounting hemispheres on the mounting plate of the klystron (see Fig. 10-2). The mounting yoke, in turn, has three accurately located V-blocks in which the hemispheres are set, thus giving complete control for the alignment of the klystron output waveguide with respect to the permanent waveguide system installed in the klystron gallery. A total vertical motion of a few

Figure 10-2 Cutaway view of Stanford klystron in permanent magnet (No. 135-5-D).



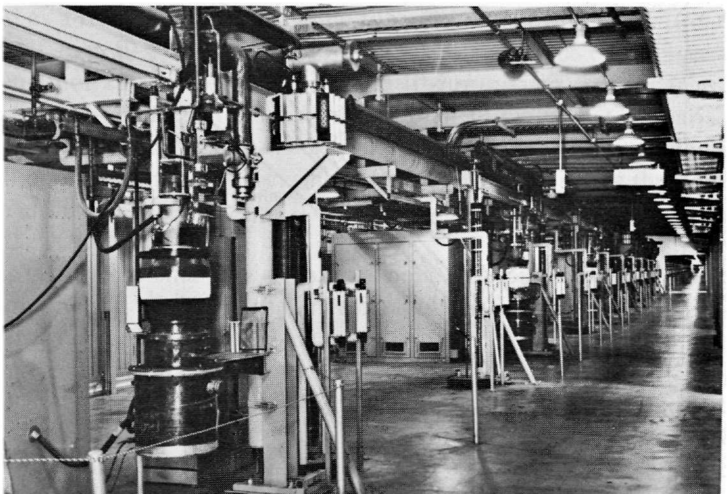
inches, controlled by hydraulic jack, enables one to lower and raise the tube until the flange mates with the corresponding flange of the waveguide system. The whole klystron assembly, consisting of the tube and the pulse transformer tank, is brought into location on an "air-bearing" platform so that the locating hemispheres and V-grooves can easily be mated.

A combined vacuum and RF joint is made at the waveguide output flange by means of a rectangular copper gasket. The flange design is different from that used for other waveguide joints on the accelerator because of the high temperature of the flange during the baking of the tube. Little difficulty has been experienced in obtaining a satisfactory leak-free joint at the output flange.

The klystron body and the permanent magnet are bolted to a spool piece, the upper end of which is the mounting flange (see Fig. 10-2). The permanent magnet, in turn, is built with supporting stainless steel rods between the upper and lower pole plate and a flange welded to the magnetic shield to which the pulse transformer tank assembly can be connected. It was fortunate that the Electronics Department was able to procure a pulse transformer of much smaller dimensions than had been previously achieved at these operating voltages and powers. As a result, the overall height of the klystron-pulse transformer tank assembly varies from 6 to 7 ft, depending on the specific tube length. Figure 5-16 is a photograph of the klystrons supplied by the various manufacturers, mounted on pulse transformer tanks. Figure 10-3 shows a typical klystron installation in the klystron gallery.

One more design point has not been covered; it concerns the lead shielding required to keep radiation levels below a specified maximum value (3 mR at a distance of 3 ft from the tube). The majority of the tubes now installed have

Figure 10-3 Typical klystron installation in klystron gallery.



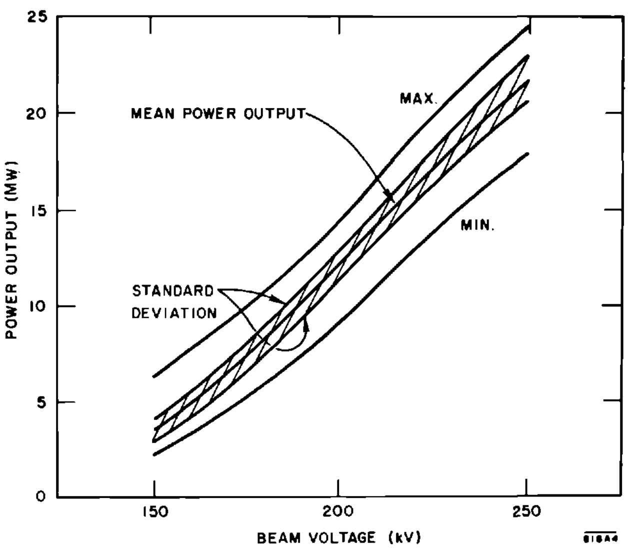
$1\frac{3}{4}$ in. thickness of lead shielding around the collector and 2 in. of lead shielding above the collector. Calculations have indicated that between $1\frac{1}{4}$ and $1\frac{1}{2}$ in. of lead is probably adequate collector shielding.

In addition, there is a $\frac{1}{2}$-in. cylindrical lead shield inside the magnet extending down approximately to the top of the high-voltage cathode bushing. In general, the shielding provided in this fashion is adequate, except for radiation coming out parallel to the output waveguide or to the water-cooling connections. Additional shielding has been provided around these areas and the radiation level meets the specifications. After a few months of operating experience, some radiation appeared to be escaping around the pulse transformer tank, and a small quantity of lead shielding has been added to keep all tubes within specifications.

10-6 Klystron performance (JVL)

In spite of early difficulties encountered by the vendors, all tubes operating on the accelerator meet the minimum specifications. Figure 10-4 shows the power output versus beam voltage for all tubes installed as of November 1966. The mean power output is approximately 12 MW at 200 kV and 21.7 MW at 250 kV. The standard deviation is from 11.4 to 12.8 MW at 200 kV and from 20.6 to 23.0 MW at 250 kV. Accordingly, there is no question that the electrical performance is entirely satisfactory from a power output standpoint. Similarly, the gain requirement has been met or exceeded in all cases, and the stability is generally excellent. However, it is difficult to give statistical information on these parameters.

Figure 10-4 Average performance of installed klystrons in November 1966.



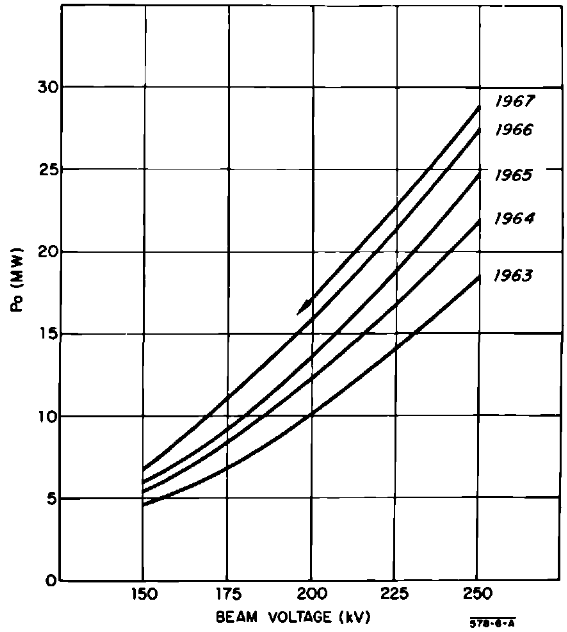


Figure 10-5 Comparison of SLAC klystron performance in electromagnet. Drive and focusing optimized at each voltage.

Although the present performance of all tubes on the line is eminently satisfactory, a brief review of the experimental results obtained during the development program is probably in order.

Figure 10-5 shows the improvement in performance of experimental tubes built at SLAC when operated in electromagnets. The improvement can also be expressed as a function of experimental tube type as shown in Fig. 10-6. A comparison of Fig. 10-6 with Table 10-2 indicates the effect of changes of drift tube length on tube performance. Figure 10-7 shows the performance of the XM-7 and XM-12 tubes in "standard" permanent magnets. Comparison of Figs. 10-6 and 10-7 shows that the power output of the XM-12 design at 250 kV with permanent magnet focusing is less than 1 MW below the power output with electromagnet focusing. The difference in these outputs is about 3 MW for the XM-7 design.

The reason for this smaller decrease in power output of the XM-12 is obvious upon analysis of the magnetic field plots (see Fig. 10-8). Curve 1 of Fig. 10-8 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. 10-8. With the permanent magnets commercially available at present, it does not appear feasible to obtain fields similar to that of curve 2 in Fig. 10-8.

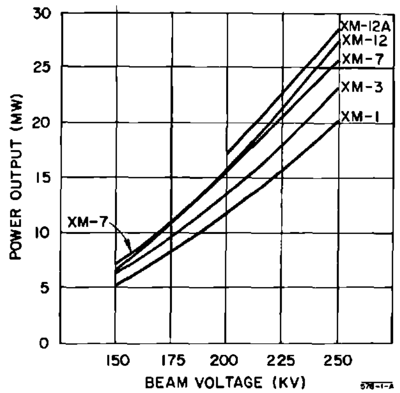
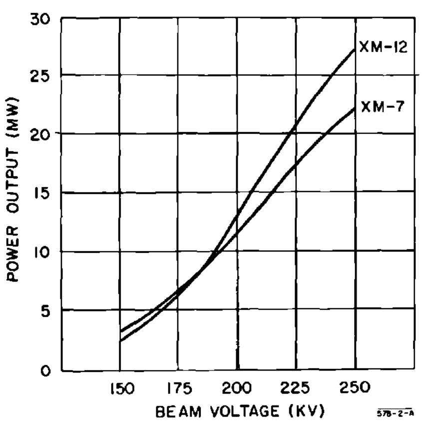


Figure 10-6 SLAC klystron performance in electromagnet. Drive and focusing optimized at each voltage.

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 tube performance.

Accordingly, experimental tubes (XM-12) were built with the third and fourth drift diameters increased from $1\frac{1}{8}$ to $1\frac{1}{4}$ in., but with all other parameters equal to those of the XM-7 tubes. Upon test in electromagnets, both tubes exhibit performance essentially equal to that of the best XM-7 tubes (as shown by curve XM-12, Fig. 10-6), but the magnetic field requirements had been drastically reduced as indicated by curve 3 of Fig. 10-8. These tubes were

Figure 10-7 SLAC klystron performance in permanent magnets.



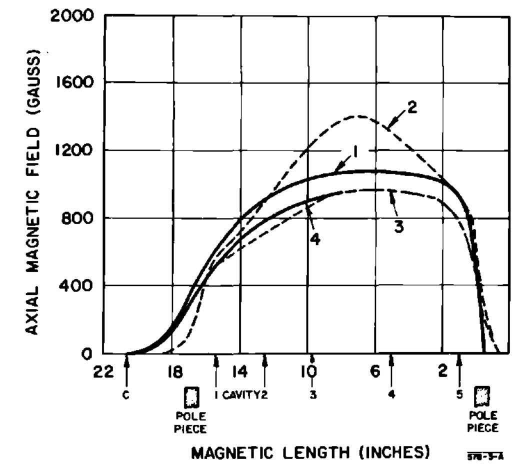


Figure 10-8 Axial magnetic fields for SLAC klystrons.

then tested in permanent magnets which had been demagnetized by approximately 100 G from their standard value. The actual magnetic field plot is given by curve 4 of Fig. 10-8 and the average performance of the XM-12 experimental tubes in a permanent magnet is shown in Fig. 10-7. By comparing Figs. 10-6 and 10-7, it can be seen that their performance in permanent magnets is substantially the same as in electromagnets at the higher-voltage levels.

One experimental tube has been built with the XM-12 dimensions, but with the output gap length decreased from approximately 1 to approximately 0.8 rad. The performance of that tube in an electromagnet up to 250 kV is shown in Fig. 10-5 (1967) and Fig. 10-6 (XM-12A). In a permanent magnet, the same tube produced almost 28 MW at 250 kV. Other tubes will be built with similar modifications to prove whether or not the observed improvement can be duplicated.

A serious effort was made to improve tube efficiency by taking advantage of extended interaction cavities. The first tubes built in this fashion had slightly higher output than the standard tubes built at that time (XM-7), but the extended interaction cavities tended to produce oscillations which could only be eliminated by extremely critical focusing adjustment. Although it is theoretically possible to achieve higher performance with an extended interaction tube, the necessity of extremely stable output of the klystron used on the accelerator may render the extended interaction klystron design impractical.

For these reasons and in view of the efficiency improvements already achieved, the effort is now concentrated on further improvement of the standard klystron. It appears that the drift distances are not yet fully optimized. One limitation at present is the overall length of the magnetic field. However, it appears feasible to operate klystrons at these power levels with magnetic field reversal. This would eliminate the restrictions on total drift distances.

In addition, the possibility of building tubes for higher-power output is being examined. One experimental tube (XM-12A) has been operated up to 300 kV in an electromagnet. At that level, the tube was producing in excess of 40 MW at 45% efficiency. The same tube in a specially shunted permanent magnet was also operated to 270 kV with a power output of 34 MW and an efficiency of approximately 42%.

10-7 Window development (JHJ)

The window effort at SLAC has been a continuation of work which started at Stanford University with the design of the first high-power klystrons which were used on the Mark III accelerator. Additional window studies were done in connection with the construction and operation of the Mark IV accelerator and in conjunction with other high-power tube work at the W. W. Hansen Laboratories of Physics, Stanford.[3,13] It seems desirable to present briefly some of this initial work to put the present studies in proper perspective.

Breakdown and overheating of the output windows has been common during the operation of all high-power klystrons. In the first Stanford experimental high-power klystron representing a power extrapolation 1000 times that available from existing klystrons of that era, the window problem was avoided by constructing the tube with a load as an integral part of the vacuum envelope. Somewhat later, as had been feared, the first output window (a resonant glass window from a commercial magnetron) failed, and a series of designs were then tried, all of which had very short lives. Finally a 3-in. diameter alumina disk in a pillbox structure* was developed which performed reasonably well.[14] When this model was mounted so that secondary electrons from the output cavity of the klystron could not directly strike it, window life of the order of cathode life was achieved (approximately 1500 hours). These klystrons were operated on the Mark III accelerator at levels of approximately 15-MW peak and 2-kW average power. Because these tubes were continuously pumped, a small leak could be tolerated, and it was possible to replace windows by keeping the tube filled with dry nitrogen during the change. The dominant mode of failure of these windows was by puncturing through the ceramic. Although cracking occurred, it always appeared on windows which had been badly damaged by punctures. The windows became darkened on the load side by carbon deposited from the diffusion pump oil vapors in the system. Life data on these windows had an exponential distribution, indicating that their failure was random and independent of previous history.†

Because radiation from the klystron and the awkward geometry cause

* Similar to Fig. 10-9.

† More recently the Mark III accelerator has been operated in a mode in which the power from the klystrons is always reduced to a low value after a load breakdown. The power is then slowly raised to full value. This operating change has increased window life to well over 10,000 hours. The data on these recent window failures are understandably too scanty to indicate a statistical trend.

difficulties in testing windows on tubes, and because of the high cost of such tests, a resonant ring was built to facilitate these studies.[15] The ring also made it possible to test windows at powers far above those available directly from a klystron. This ring was pumped to about 10^{-5} torr by an oil diffusion pump with a liquid nitrogen trap. A viewing port allowed observation of one surface of the window. Although much was learned about the glow observed on the surface of all windows tested, no windows failed in ring tests at the power then available (25 MW peak).

To summarize the window status as of 1960: At the Mark III facility it had been found possible to make a window which would withstand 15-MW peak and 2-kW average power and which would have a reasonable life. There were still many window failures due to punctures, but techniques had been developed to allow replacements of windows on operating tubes. No design had been found which was superior to the initial pillbox construction, and alumina from different manufacturers gave essentially identical performance. Tests with 50% greater peak power than used on the Mark III had failed to damage windows.

The SLAC window program

Because new window problems were foreseen at SLAC power levels, which are 50% higher in peak power and 10 times higher in average power than the Mark III requirements, a program to study window failure mechanisms was started in 1958. It was hoped that the mechanisms causing window failures could be identified and that designs and operating conditions could be specified which would give long window life. A testing program was also set up to evaluate promising window materials by testing them to destruction. In the course of this program, excessive heating caused by multipactor at the window surfaces was recognized, and a study of methods of eliminating this effect was started. Some work was also done on window matching techniques and on the optimum window structure for SLAC use.

Test apparatus

Initially the diffusion pumped ring, described above, was used to test completed window assemblies. A more powerful driver tube was used giving ring powers between 70 and 80 MW peak, and average powers up to 45 kW. Because vacuum-tight window assemblies are expensive and time-consuming to make, a method of shrink-fitting window materials into copper (or copper-plated stainless steel) sleeves was devised. Although the dielectric-to-metal joint is not vacuum tight, it is very good from an RF standpoint. This technique allowed testing of materials for which sealing techniques did not exist and eliminated possible degradation of performance caused by a standard metal-to-ceramic type seal.

To allow testing at higher powers and to investigate the effect of better vacuum conditions, an all-metal ring was built incorporating a number of improvements.[16] It was pumped by a sputter-ion pump which eliminated contamination by oil vapors and achieved pressures of 10^{-8} torr at the window (without RF). Extensive water cooling was provided to reduce the detuning effects of heating at high powers. The ring was equipped with two viewing ports to allow both surfaces of the test window to be observed. Two ionization gages measured the pressures close to both sides of the window. This ring was initially baked to reduce contamination to a minimum. It was hoped that each window assembly could be baked with the ring prior to testing. This procedure proved to be too difficult and time-consuming, but good vacuum conditions were maintained by using clean window assemblies, keeping the ring pumped except when making window changes, and by always letting up to dry nitrogen. When the ring was driven by a SLAC klystron, powers up to 170 MW peak and 150 kW average were attained.

Because, in a resonant ring, windows are tested with a traveling wave that is essentially reflection-free under high gain conditions, an all-metal ion-pumped cavity was built to evaluate possible differences in window behavior in highly mismatched cases.[16] Because of its high Q, this cavity proved very difficult to keep well matched and in tune. It was used for a relatively small number of tests. The behavior of samples in this cavity was very similar to that observed in rings.

Both the rings described above were carefully matched without test windows. The windows were separately tuned before insertion into the rings, eliminating the need for expensive impedance matching transformers in the rings. When needed, a small amount of matching could be done by squeezing the waveguide near the test piece or by shifting the frequency slightly. Using these procedures, it was relatively easy to keep the rings in good tune as the power was raised or as the losses changed.

At high peak powers, a considerable quantity of x rays are generated within the ring, particularly at the test window and at other discontinuities such as the tuner. It was found necessary to provide some lead shielding and to place lead glass in front of the viewing ports. It was also found that power at harmonic frequencies came either from the driver klystron or from generation within the ring, making it necessary to provide metal screens on the viewing ports to avoid possible eye injury.

Choice of window materials

Probably the most stringent specification for the SLAC klystron windows is the requirement for a vacuum environment on both sides of the window. This completely eliminates convection gas cooling commonly used on high-power windows and allows multipactor heating to occur on both sides of the disk. Radiation cooling is negligible until the window has reached temperatures where most materials will fail due to thermally induced stress. Therefore, the loss tangent in the window material must be as small as possible, and the thermal conductivity and the tensile strength should be as high as possible.

Since the fields are high, the dielectric strength should also be high.[17] In addition, the material must be capable of being assembled into a vacuum-tight, bakeable seal of high reliability.

Table 10-3 lists a group of dielectric materials which were considered promising for window use.[18] With the exception of beryllia and pyrolytic boron nitride, all have very poor thermal conductivities. The loss tangent, with several exceptions, is sufficiently low to allow use at SLAC powers. A few of these materials present practical problems which preclude their use, as long as other suitable materials are available. Although quartz has a very low dielectric loss tangent, its thermal conductivity is also very low. It is very difficult to seal quartz to metals because of its very low thermal expansion coefficient. Pyrolytic boron nitride had not been made into vacuum-tight seals and was not readily available. Sapphire, due to its anisotropic nature, must be used in zero-oriented form which makes it expensive. It is also a difficult material to make into large vacuum seals because of its tendency to crack.

At peak powers above 35 MW, many windows failed by puncturing during ring testing. In addition, some failures by cracking occurred at average powers over 2 kW. Many of the windows on experimental klystrons (including both alumina and beryllia) also cracked at powers as low as 6 kW. A large number of samples of alumina from one commercial source were tested to destruction to determine the mechanism of failure. These tests revealed a general pattern for two types of failure.

One type, dielectric breakdown within the material, occurs when the *peak* power reaches a critical value which is apparently determined by the individual sample. The second type of failure occurs when the *average* power through the window exceeds a critical level. The window usually fails by cracking in a manner controlled by the constraints at the edge of the disk. In a few cases, a single puncture directly through the disk has been found. In all tests, some glow appears at the surface of the window, either as a bright oval at the center of the disk or as a fainter set of arcs the shape of which is determined by the power level and the intensity of which decreases during the test.

Table 10-4 shows the results of a series of tests done on window materials. The following standard testing procedure was used. At a 60-cycle pulse rate and a 2.5-μsec pulse length, the peak power was raised to the maximum available (70–90 MW) or until dielectric failure occurred. The power was reduced to a low level while the pulse rate was increased to 360 cycles, after which the power was again raised to the limit of average power available (40–45 kW) or until thermal failure occurred (by cracking or melting). These tests were done with samples shrunk into sleeves to eliminate any effects from sealing techniques. All samples were tested in a pillbox-type geometry.*

* The cooperation of manufacturers of these dielectrics contributed greatly to the success of these tests. In particular, Western Gold and Platinum, Union Carbide, and Norton Refractories have supplied courtesy samples of materials made by them for evaluation.

Table 10-3 Physical properties of window materials

Material	*Manufacturer*	*Dielectric strength (V/mil)*	*Dielectric constant*	*Dielectric loss factor*	*Thermal conductivity (cal/cm²/sec/°C)*	*Thermal expansion coefficient (°C)⁻¹*	*Tensile strength (psi)*	*Compressive strength (psi)*	*External strength (psi)*
Alumina									
AL-300	Wesgo	1100[a]	9.4[b]	0.005[b]	0.064	8.5×10^{-6}	—	250,000	46,000
AL-995	Wesgo	800[a]	9.4[b]	0.002[b]	0.070	6.9×10^{-6}	—	300,000	62,000
AD-96	Coors	220–240	8.9	0.073	0.048	3.7×10^{-6}	26,000	300,000	49,000
AD-99	Coors	220–240	9.4[b]	0.002[b]	0.070	3.5×10^{-6}	34,000	300,000	54,000
4462	Frenchtown	225	9.2	0.003	0.071	6.11×10^{-6}	—	425,000	55,000
Sapphire	Linde	1700	9.4[b]	0.002[b]	0.06	7.7×10^{-6}	58,000	300,000	65,000
Beryllia BD-96	Coors	238	6.6	0.003	0.60	9.23×10^{-6}	—	225,000	32,000
Fused quartz									
Amersil	Engelhard	410	3.72[b]	0.001[b]	0.0033	0.54×10^{-6}	7,000	190,000	—
Boron nitride									
Hot-pressed	Union Carbide	300	4.78[b]	0.0015[b]	0.045	0.33×10^{-6}	—	—	15,000
Pyrolitic	Union Carbide	>3000	5.12[b]	0.0005[b]	0.15	0.1×10^{-6}	—	—	15,000
Magnesia	Norton	—		—	0.100	—	—	—	—
Zirconia	Norton	—	~20	—	0.02	9.1×10^{-6}			2,300
Pyroceram 9606	Corning	—	5.8	0.002[b]	0.009	5.7×10^{-6}	—	—	20,000[c]
Glass	Corning	900	4.1	0.01	—	3.2×10^{-6}	—	—	~10,000[c]

[a] Measured in oil.
[b] Values are at 3 to 6 GHz and were taken from Reference 23. (All other values are quoted from manufacturer's data sheets.)
[c] Surface abraded.

Table 10-4 Comparative material test data

Material	Samples tested	Surviving samples[a]	Failure samples: Dielectric failures	Failure samples: Thermal failures	Remarks
Alumina Untreated	46	13	18	10[b]	Multipactor on 60% of windows tested
Grooved	7	1	4	2	Multipactor reduced, more susceptible to dielectric failure
Grooved and coated	7	3	4	—	No multipactor, still susceptible to dielectric failure
Beryllia	1	0	—	1	Multipactor
Quartz					
Flat	5	0	—	5	Multipactor-heating, high-temp. gradient, catastrophic failure
Grooved	6	5	1	—	Only failure during mismatch at 80 MW, no multipactor
Boron nitride					
Hot-pressed	8	0	8	—	No multipactor
Pyrolitic	3	1	2	—	Interlaminar breakdown in two samples,[c] new sample survived
Magnesia	5	0	5	—	Most failed at low peak power (<7 MW)
Zirconia	3	0	—	3	All failed at low average power ($\approx$2 kW)
Pyroceram 9606	2	0	—	2	Melted at $\sim$30 kW average power (loss apparently related to reduced resistance)
Glass 7070	2	0	—	2	Melted at average power $\leq$10 kW

[a] Surviving maximum available powers $\geq$ 70 MW peak (1.8×10^{-4} duty factor) and 40 kW at 1.08×10^{-3} duty factor.

[b] Five samples which were not tested at high average power had been damaged by severe multipactor during peak operation and would most likely have failed thermally.

[c] Very early experimental samples.

These tests showed that multipactor can be expected on all uncoated materials except possibly boron nitride. They also indicated that the best thermal conductivity available (beryllia) is not sufficiently high to prevent thermal failure. Poor thermal conductivity, however, results in catastrophic failure. Glass (7070), Pyroceram, and zirconia, tested because of their high dielectric strength, melt at low powers due to their high loss tangents. Both magnesia and hot-pressed boron nitride were found to be unsuitable for SLAC use because of low dielectric strength. Boron nitride (in the pyrolitic form) would possibly be suitable if sealing techniques could be devised. Quartz, treated to prevent multipactor, shows promise, but suffers from the same sealing problem and has been found to be highly variable from sample to sample. Sapphire, not shown on this chart, was tested in a cavity where the samples failed by cracking at disappointingly low powers. Similar low resistance to thermal shock has been found at the W. W. Hansen Laboratories of

Physics, Stanford, during attempts to make sapphire-to-metal seals. Thus, alumina and beryllia, treated to prevent multipactor were found to be the two most promising materials tested. There has been a continual improvement in dielectric materials, such as alumina, concurrent with their use in power tubes. It should be stressed that the data presented here show the performance of the materials available at the time of the tests.[18] Improvement in material and different conditions of operation (i.e., with gas under pressure on the load side of the window) may allow use of substances not suitable in the SLAC environment.

Although low dielectric constant is desirable from the matching standpoint, the only factor of major importance for SLAC windows is the ability to handle the output power. Although beryllia would appear to be desirable because of its greater thermal conductivity, uncoated samples of beryllia have failed on klystrons at as low an average power as have alumina. Beryllia is also a difficult material to handle because of its high toxicity in powder and vapor forms. Therefore because alumina coated with titanium had been shown to handle more than twice the power needed, this material was chosen.

Design of window assemblies

Many high-power window designs have been employed at Stanford and in the tube industry.[3,6,13,19–21] Half-wave blocks of material, while attractive from the matching standpoint, have been avoided because of difficulties in construction. Slanted slabs and conical designs, which provide a bandwidth which is not needed at SLAC, all have two-surface multipactor problems which cause excessive heating. All of the above designs may also have ghost modes[22] and trapped resonances which can cause dangerously high fields. In the simple narrow-band pillbox structure, such modes can be placed well away from the operating frequency. The relatively thin ceramic disk can be readily and reliably sealed into a suitable metal sleeve. Variations of the pillbox design, such as increasing the spacing between the window and the transitions, were tried at the Mark III accelerator[14] without improving performance.

Some of the first experimental klystrons built at SLAC were constructed with two identical output windows to reduce the chance of failure by halving the power each must handle. This system did not prove any more successful than a single window, and the two outputs only added to the complications of testing. All SLAC-built klystrons now use a single output window* of the pillbox type shown in Fig. 10-9. A high-purity alumina disk, A, is copper brazed into a cupronickel sleeve, B. The sleeve is brazed to a stainless steel cylinder designed to mate with two special flanges, thus forming a complete demountable window assembly. Vacuum sealing is provided by copper gaskets located between the cylinder and the flanges. The window is matched by proper choice

* Designed by G. K. Merdinian.

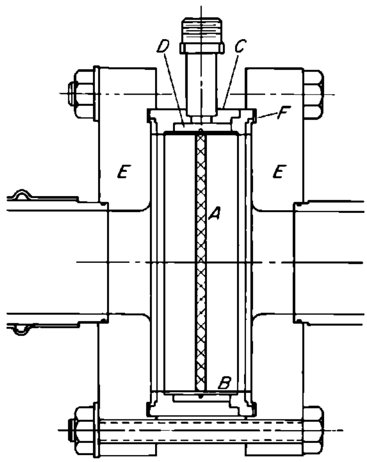


Figure 10-9 Window used on SLAC-built klystrons.

of dimensions and by using the reactance produced by the discontinuity between rectangular and cylindrical waveguide; the resulting VSWR is less than 1.04. The alumina disk is coated by sputtering with titanium after it is brazed to the sleeve assembly, but before it is bolted onto the klystron.

Of the four klystron vendors, three (RCA, Litton, and Eimac) have used a pillbox type of window design similar to that described above. In two of these the ceramic is brazed into a cylinder. The third design (RCA) uses a technique in which the disk is shrunk into a thin copper cylinder surrounded by a band of high tensile strength steel. The force produced presses the ceramic sufficiently far into the copper to produce a vacuum-tight bakeable seal. This force is great enough to cause the ceramic disk to become slightly dished. The fourth vendor (Sperry) has chosen a design using a disk slightly greater than a half-wave length thick. It is a modified pillbox and is water-cooled. All of these designs use the discontinuities at the junction between the two types of waveguide as part of the provisions for matching. All vendors use alumina and have developed coating processes to prevent heating by multipactor. These different designs, when properly made, have operated successfully on the SLAC accelerator.

10-8 Types of window failure (RWB)

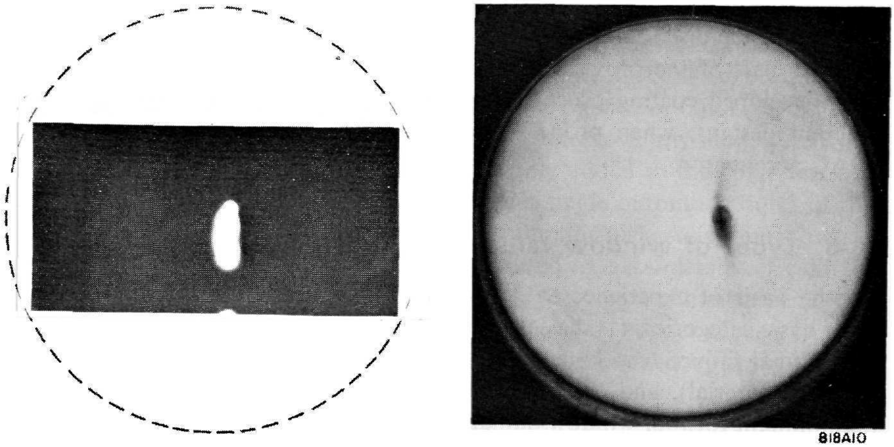
On the basis of experience to date, window failures can be separated into three basic categories: (1) dielectric failure (punctures and/or internal failure), (2) thermal failure (cracking or melting caused by excessive heating of the window material), and (3) boundary failure. Thermal failure has been the predominant form of window damage on SLAC klystrons. In many instances a window failure cannot easily be classified in one of the three groups, but will combine the symptoms of two or more types. In such cases, the question of which failure mechanism occurred initially is often difficult to resolve.

Dielectric failure

Dielectric failure occurs in a window when the electric field gradient exceeds the dielectric strength of the window material and the ensuing electrical breakdown causes permanent damage to the material. The path of the breakdown may be entirely confined within the dielectric in the case of internal failure or may extend from the dielectric to the adjoining medium in the form of a puncture. The two types of failure are usually found together since the occurrence of one will often immediately initiate the other.

Internal failure may be expected to follow the direction of maximum dielectric stress, as determined by the electric field configuration in the propagating mode. This form of dielectric failure determines the ultimate limitation of any window material. Since the computed electric fields present in SLAC windows are below[16] the published value of dielectric strength[23] of the alumina used, internal failure should not be a problem. Internal breakdown did occur occasionally in higher-power tests performed in the window study program. Internal failure in process and the damage resulting from it are shown in Fig. 10-10a and b, respectively. The cause of internal failure where electric fields in the propagating mode do not exceed the intrinsic dielectric strength has not been established, but two possible explanations have been postulated. The presence of randomly occurring voids in the body of the window material is believed to increase the probability of internal breakdown. Consistent dielectric failures observed at relatively low-power levels in a

Figure 10-10 (a) Internal failure (view of a failure in process). (b) Internal failure (view of the damage caused, lighting from behind).



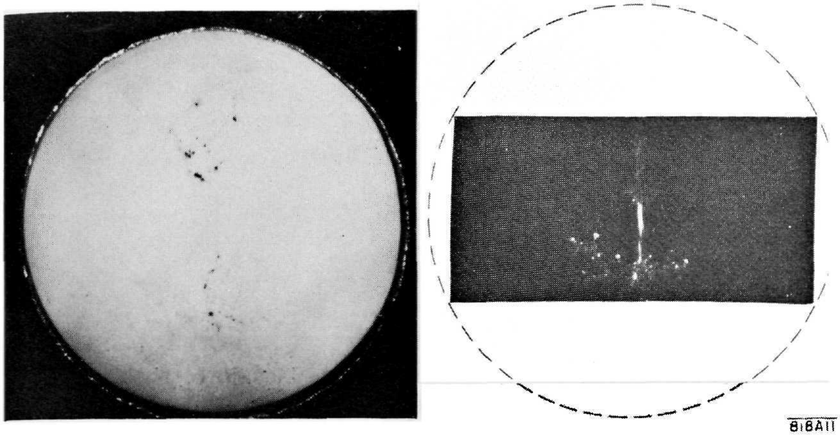


Figure 10-11 (a) Window punctures (Mark III window). (b) Surface discharge.

group of alumina specimens known to include voids gave some weight to this hypothesis. One possible mechanism for this form of failure has been described by Nergaard.[24] Another possible explanation involves the presence of "ghost" modes[22] in the dielectric or "trapped" resonances in the window structure, either of which could produce electric field gradients considerably higher than those in the propagating mode.

The more common form of dielectric failure at SLAC and at the Mark III accelerator has been puncturing, as illustrated in Fig. 10-11a. The exact nature of the puncture mechanism is still unknown, but several possible explanations have been advanced. Both the presence of voids and the effect of spurious resonances could account for puncturing as well as for internal dielectric breakdown. Occasional punctures appear to be related to surface discharge phenomena of the type shown in Fig. 10-11b. Breakdown in this manner is frequently observed on windows operating at high peak power and does not often damage the dielectric. There are indications that multipactor may also contribute to puncture formation, but the mechanism involved is not yet understood.

Thermal failures

The thermal failure category includes all window damage caused by excessive heat produced in the window material. Thermal damage may consist of melting or cracking of the dielectric. With some exceptions, melting is usually caused by violent electrical breakdown at the window. In most cases of failure, the window cracks when stresses due to temperature gradients exceed the mechanical strength of the material. Because of the mechanical properties common to most dielectric materials (see Table 10-3), windows crack under tension. In the SLAC window, which is brazed into a thin metal sleeve, failure occurs when the temperature gradient from the center to the edge of the

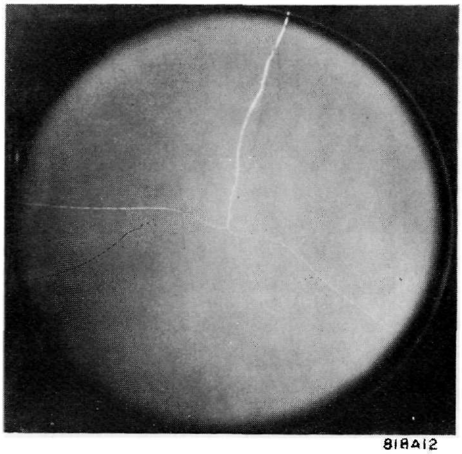
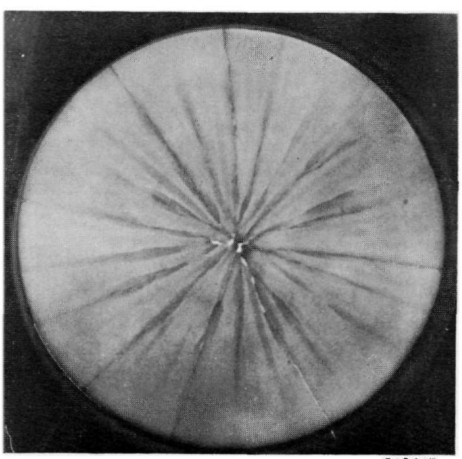


Figure 10-12 Typical example of a SLAC window cracked due to overheating (lighting from behind).

window produces tensile stress circumferentially. In cases where heat loss is relatively uniform, a window will usually crack in a pattern similar to that shown in Fig. 10-12. A special case is that of a vendor tube window mounted in a compression seal, to bow the ceramic. In this configuration, mechanical failure often begins at the center where a tensile force tangential to the surface is produced as the window heats, and the compressive forces at the boundary of the disk increase the dishing of the ceramic (see Fig. 10-13).

Figure 10-13 An example of the mechanical failure of a window in a compression seal (lighting from behind).



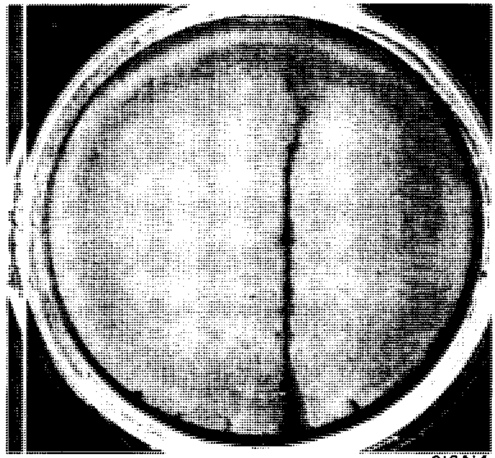
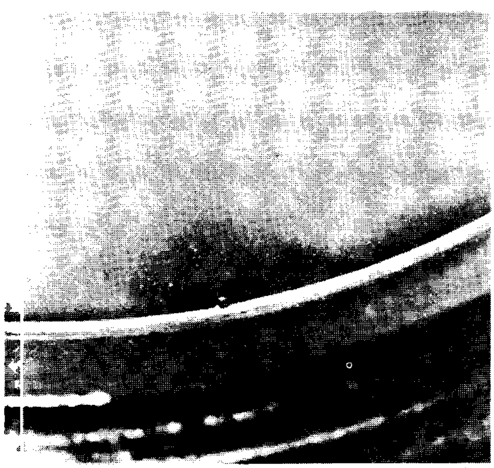


Figure 10-14 Window cracked because of a seal failure.

Cracks may also be caused by local thermal stress, and will often occur in cases of dielectric or seal failure (see Fig. 10-14). In the former instance, it may be difficult to determine which type of failure occurred first. Usually, in cases where the window cracks first, punctures which may then appear as a secondary effect will all be located on the crack (as in Fig. 10-15). Where dielectric failure precedes cracking, punctures will often be scattered randomly on the window surface, many of them far removed from any crack

Figure 10-15 Seal failure in early stage of development. (Magnified approximately 4 times.)



which may result from thermal stress produced at the site of a particularly active puncture.

The classification of thermal failure can also be subdivided according to the method by which the dielectric is heated. Four identifiable sources of window heating are: dielectric loss, electrical breakdown, multipactor, and resistive loss in a coating layer. The latter two are discussed in the section on the multipactor effect and its suppression. The heat-producing effects of electrical breakdown have been described in the foregoing treatment of crack formation.

Excessive heating due to dielectric loss has not been a primary problem with SLAC windows. The relatively low duty factor (0.9×10^{-3}) of the klystron output and the low dielectric loss factor of the alumina ceramic used as window material have combined to confine dielectric loss heating within safe limits,* despite the relatively poor heat transfer capability of the SLAC window design. An aspect of dielectric loss heating is the possibility of "runaway" heating due to an increase of the dielectric loss factor with increasing temperature.[21]

Boundary failure

The final classification of window failure concerns phenomena which depend not on the window itself, but on the boundary region between the dielectric and the metal sleeve containing it. Boundary failures can be further broken down into those associated with flaws built into the ceramic–metal seal and others caused by the presence of foreign matter at the seal boundary in an area of high electric field. The problem of avoiding flaws in the ceramic–metal seal is strictly a question of proficiency in fabrication techniques. The technology of metal–dielectric seals has been extensively studied and reported.[26,27] One potential source of seal trouble is excessive penetration of the dielectric by the metalizing material. This condition can cause severe heating at the seal and possibly lead to thermal failure.[28] A fillet of brazing material should not be allowed to encroach on the surface of the window because an electrical discharge may start at the fillet. The discharge will gradually sputter additional metal onto the window surface, electrical activity will be increased in turn, and the cumulative effect will eventually produce a thermal failure. A large fillet will simply accelerate the process.

Some boundary failures have been caused by accumulation of foreign material in high field areas of the seal. The electrical breakdown which results is similar to that associated with a protruding braze fillet, as is the typical cumulative development to eventual failure. Figures 10-14 and 10-15 show two illustrations of this type of trouble, one of which depicts a thermal failure.

* The center-to-edge temperature gradient produced by the transmission of 20-kW average power through the SLAC window calculated from an expression derived by Caryotakis[25] is ≈ 10 C. The value corresponds well to measured gradients. The gradient should be expected to vary linearly with power transmitted.

The other illustrates an early stage of development of failure. If recognized in time, this condition can often be corrected simply by cleaning the contaminated and sputtered portion of the window surface. This type of damage can be prevented by careful tube handling procedures. The external surface of the window must be inspected and cleared of all contaminants each time the klystron is installed.

10-9 Window multipactor and suppression techniques (RWB)

A significant recent improvement in high-power microwave tube window development has been the use of thin film coatings to reduce secondary emission and thus prevent electron multipactor. Prior to the use of window coatings, SLAC klystron windows often failed because of multipactor heating at average power levels as low as 2 kW. Effective coating techniques have virtually eliminated the window multipactor problem.

Description of multipactor

Electron multipactor is produced by secondary electron emission in an alternating electric field. The phenomenon requires a secondary electron emission coefficient greater than unity to maintain itself and rapidly builds up to avalanche proportions at high frequencies, if certain resonance conditions obtain. In its most common form, multipactor occurs between two surfaces (which serve as terminals of the alternating field) wherever the voltage and distance between the two surfaces combine to produce a secondary electron transit time equal to one-half period at the operating frequency.[29] However, multipactor may be a single-surface phenomenon in the event of transverse electric fields as on the SLAC klystron window. As first described by Priest and Talcott,[30] single-surface multipactor is a secondary electron resonance between portions of a dielectric surface parallel to the alternating electric field. The resonance is maintained by a restoring force which returns energetic secondaries to the window surface after they have been accelerated by the RF field. The energy of the returning secondaries is dissipated upon impact producing heat in the window material and releasing photons as well as new secondary electrons from the window surface.

Recognition of multipactor symptoms

In view of the damaging potential of multipactor, it is important that its presence be recognizable. Multipactor is most easily distinguished by its visible symptoms and by the elevated window temperature it induces. Apart from multipactor, high window temperature can also be caused by dielectric loss or resistive loss. Since dielectric loss is predetermined by the choice of window material, there is little danger of its being confused with multipactor heating. In window operation at SLAC, the more likely alternative cause of window heating has been surface resistance loss, which is readily distinguishable from multipactor by visual observation of the window surface.

The visible characteristic of multipactor is the illumination produced at the window surface by the electron bombardment. This "multipactor glow" can be confused with another light-producing window phenomenon apparently associated with the release of adsorbed gas from the window surface. The "gas release glow" is much less intense than multipactor glow, depends upon the electric field configuration in the propagating mode, varies its shape with changing field strength, and has a diffuse appearance which gives the impression that the glow has depth. The gas release glow has a tendency to diminish and eventually disappear with continued operation, apparently indicating its relation to adsorbed gas.

In contrast with the gas release phenomenon, multipactor glow is much more intense and seems to emanate from the window material itself, giving the impression of a distinctly detailed pattern of illumination. In general, multipactor glow has a central pattern, most intense where electric field is highest, but is also somewhat affected by window geometry. Multipactor glow may also assume irregular shapes in instances when the surface has not been uniformly coated or when portions of a coating have been removed, as by an electrical discharge. Multipactor and gas release glow may appear simultaneously, but the intensity of the multipactor glow is likely to obscure the dimmer gas release pattern superimposed upon it.

Multipactor suppression techniques

The problem of suppressing or reducing electron multipactor has been solved by the use of thin films of materials with low secondary emission coefficient deposited on the window surface. Other techniques for reducing multipactor have been devised or suggested, but to date none has proven to be as convenient or effective as coating. The principle involved in window coating is simply a matter of superimposing a surface whose secondary emission coefficient is less than unity over the surface of the untreated window material which has a high secondary emission ratio. Only a very thin layer (≈ 50 Å) of coating film is required effectively to substitute the surface characteristics of the coating material for those of the window substrate. Because such a minute amount of coating is required to suppress secondaries, the bulk properties of the substrate material are not significantly affected. Coatings may be applied by a variety of methods most of which are variations of sputtering or evaporation of the coating material.

Multipactor prevention techniques other than coating include the use of superimposed electric or magnetic fields or of shaped electric fields. A number of alternative techniques are described in reports on window study programs conducted at Eimac[31] and Sperry.[32] One interesting possibility, the use of grooved windows, was the subject of a series of tests at SLAC in collaboration with Dr. O. Heil of Eimac. Grooved specimens of alumina and quartz were tested at high power and the amount of multipactor was compared with that observed on coated and uncoated windows with flat surfaces. With the window grooves oriented perpendicularly to the main component of electric field in the propagating mode, multipactor was greatly reduced on grooved alumina windows, although a significant amount of electron activity continued to occur on the ridges of the grooves. Only when titanium coating was deposited on these ridges was the multipactor eliminated entirely. The grooved alumina windows usually failed by puncturing in or near the areas of highest electric field gradient, i.e., in the dielectric at the bottoms of the grooves. Aside from the higher fields, loose particles of alumina or other material often became lodged at the bottoms of grooves and provided circumstances favorable to local arcing which, in turn, led to puncture of the ceramic. Grooved quartz windows were somewhat more successful, operating without multipactor even without coating on the ridges of the grooves. The different comparative behavior of grooved quartz may have been due to a lower secondary emission coefficient than that of alumina or possibly to impurity coatings picked up by the quartz. Despite the good results of grooved quartz, the difficulty of fabricating a bakeable quartz window has discouraged its further consideration as a practical alternative to the present window.

Window coating

The use of titanium-based window coating films is at the time of this writing still the most convenient, effective, and widely used method of multipactor suppression. There are, however, numerous possible variations in window coatings which remain to be explored before an optimum solution can be claimed. The question of coating material is still completely open. A few materials other than titanium have been tried; none have been thoroughly evaluated. The matter of optimum coating method and thickness is also unsettled. Finally, one of the most vital criteria of an ideal coating, its stability through exposures to high-temperature cycles, is yet to be satisfied.

Because of its low secondary emission coefficient, titanium was the original choice as a window coating and is still the most widely used material.[33] The most comprehensive investigation to date of coating material alternatives, made as part of a window study at Sperry,[32] tested a variety of materials which successfully suppressed multipactor. The problem of choosing a coating material does not appear to be difficult insofar as multipactor suppression is concerned; many materials will do the job including carbon-based impurity films.* At present, the optimum choice of material seems to depend more upon its thermal stability than its secondary emission coefficient.

The question of whether evaporation or sputtering is preferable as a coating method is yet to be resolved. There is no positive evidence to indicate that

* Multipactor did not occur on nearly half of the uncoated window samples tested (see Table 10-4). Though not recognized at the time, it was later shown that a thin layer of oil film from the oil diffusion pump of the original ring could prevent multipactor completely.

either method produces a more effective window coating film. There is perhaps an advantage to be gained from better coating adherence of sputtered films, but this has not as yet been established experimentally. The coatings on SLAC klystron windows are applied by ac sputtering with a discharge between shaped titanium electrodes in an argon atmosphere.[34] Windows on other SLAC tubes supplied by vendors have been coated by evaporation from heated titanium wire or by RF sputtering.

Coating thickness is a critical variable. The minimum effective coating thickness is not precisely established, but is approximately 50 Å. Insufficient coating has not been a problem on SLAC windows. Marginally thin coating will perhaps permit enough multipactor to be easily visible, but even partial protection is usually sufficient to prevent significant multipactor heating at SLAC operating levels. Excessive coating poses a more difficult problem. Following the vacuum bake cycle, the electrical resistance of a thick coating may be reduced sufficiently to cause excessive heating due to resistive loss. Although a thin coating is identifiable by the increased multipactor glow intensity, a thick coating is indistinguishable by visual observation. Neither will temperature measurement during preinstallation test in the resonant ring usually indicate a thick coating, because the increase of resistive loss in the coating will not become apparent until its oxygen content is reduced during vacuum bake exposure. An accurate method of measuring coating thickness is, therefore, a vital adjunct to the coating process.

There are numerous thin-film thickness measurement techniques,[35,36] but few of them can be employed during the coating process. The most practicable method for measuring films deposited on SLAC windows appears to be the use of a crystal resonator as a microweighing device. Placed adjacent to the surface of the window being coated, the crystal picks up a proportionate amount of the window coating, and its resonant frequency shifts in a linear relation with its increase in mass. Unfortunately, it has not yet been possible to calibrate the crystal monitor readings against an independently determined absolute value of coating thickness. However, on the basis of experience with tube window performance and resonant ring tests, arbitrary limitations of coating thickness have been established in terms of the relative thickness readings indicated by the crystal monitors. The relative limits now being used are 80 Å minimum and 130 Å maximum. There has been a consistent tendency to lower the maximum thickness limitation as more has been learned of the instability of titanium coatings at high temperatures.

Window coating stability

The greatest single problem involved in the use of window coatings at SLAC has been their lack of stability when exposed to high-temperature cycles. With windows on klystrons built at SLAC, the problem has been limited to vacuum bake cycle exposure, but with some of the vendor tubes exposure to braze cycle temperatures in hydrogen atmospheres has also been involved.

In the case of vacuum bake exposure, the effect upon the coating is essentially one of reduction of the original coating layer to form a film with lower electrical resistance. This behavior is typical of titanium coatings but has also been observed with other window coating materials. Following application and subsequent exposure to air, a titanium coating assumes a resistivity greater than 10^{12} ohms/square. During a vacuum bake, this resistivity will decrease to 10^6 ohms/square or less, depending upon the thickness of coating. Even after cooling, the surface of the window which remains in vacuum will maintain a relatively low surface resistance which may contribute a significant amount of resistive loss to overall window heating. Only when the inside surface of the window is exposed to air will its resistance approach its initial high value. If the same window coating is again exposed to vacuum bake, the inside surface resistance will assume lower values at the bake temperature and after cooling than it did as a result of the initial bake. The ability of titanium coatings to reoxidize whenever exposed to air made it quite difficult to recognize the resistance drop caused by vacuum bake. Only when thermal failures began to occur consistently on windows exposed to two or more vacuum bake cycles was the phenomenon identified.

Comparative evaluations of window coating stability were first made by means of surface resistance measurements in simulated vacuum bake cycles. These measurements verified the mode of coating resistance behavior postulated from the observed pattern of tube window failure. Further verification was provided by means of a "double-window" test technique, in which two standard klystron windows are joined by a short section of waveguide evacuated by an independent ion pump. Using this configuration, it is possible to conduct resonant ring tests on windows exposed to vacuum bake, while maintaining a vacuum on only one side of each window. In this way the conditions of vacuum bake exposure encountered by a tube window are simulated.

Apart from the effect of vacuum bake, experience with klystrons built for SLAC by outside vendors has shown that titanium-based coatings may react with a hydrogen atmosphere at braze cycle temperatures. The effects of exposing a coating to braze conditions are much less clearly understood than are those associated with the vacuum bake, but seem to be critically dependent upon the water vapor content of the hydrogen atmosphere. A braze cycle in dry hydrogen appears to affect the coating in much the same way as a vacuum bake cycle, reducing the resistance of the coated surface and causing relatively high resistive loss heating during operation. Brazing in wet hydrogen has an entirely different effect, resulting in a noticeable increase in window multipactor, as if the coating has been partially removed.

10-10 Operational conditions (JVL)

The SLAC klystrons have been designed to be able to operate at beam voltages between 150 and 250 kV, corresponding to peak power outputs of approximately 3.5 to 22 MW (see Fig. 10-4). The tubes are capable of being turned on directly at any voltage level within that range. However, in general, after a station has been inoperative for a few days, it is the practice to turn on near the lower voltage limit and at the minimum repetition rate (60 pulses/sec). Both beam voltage and repetition rates are then increased gradually to the required operating level.

The main reasons for the slow turn-on are to protect the components of the station, including the klystron, and prevent excessive gassing in the waveguides and in the accelerator pipe which could occur after a reasonable period of idleness.

The details of the protection system are covered in Chapter 21, but the principle of the protection is based on prevention of damage to the tube components. One set of protection devices and interlocks ensures that the beam voltage cannot be turned on until adequate heater power has been established for a predetermined time, and that there is water cooling in the system. Another protection circuit prevents the repetition of arcing in the tube should such arcing occur. In the present system, a single beam fault from either cathode overcurrent or overvoltage stops the trigger to the modulator for approximately 2 sec. After that time, the beam pulse comes back on. If arcing occurs again, the procedure is repeated until a predetermined number of faults have taken place (1–15 per hour), after which the modulator stops until it is reset manually.

Since it was suspected that the window could be a major cause of klystron failures, the vacuum system for the SLAC accelerator was specified as an all-metal, ion-pumped system. It has proven extremely reliable, achieving pressures in the 10^{-8} torr range. It is believed that this good vacuum inhibits window failures, especially those which might be caused by window overvoltage due to load breakdown. In addition, two circuits were incorporated to protect the window under adverse conditions. One measures the vacuum close to the window and stops the modulator when the pressure rises above a preset level (presently 10^{-6} torr). When the pressure again falls below this level, the modulator is automatically turned on again. The second system turns off the modulator when the reflected power exceeds a preset level (now 2 MW peak). After the first outage, the klystron is turned on at full power, if conditions are normal within 2 sec. After the second outage, or if vacuum pressures remain high for more than 2 sec, the RF drive to the klystron is reduced to give a low output before the modulator is turned on again. The drive is then increased in a period of 5 to 6 sec to the value which gives full output power. This system is similar to that used successfully on the Mark III accelerator at Stanford. The maximum number of allowable vacuum or reflected energy faults is determined by the same counting circuit used for beam fault protection.

10-11 Klystron operating experience (JVL)

As of July 1, 1967, the accelerator had been in operation for somewhat more than 1 yr, in addition to approximately 6 months shakedown of individual sectors. The total klystron hours accumulated was close to one million, and the total number of failures was 130. A total of approximately 400 tubes have been accepted from outside vendors, all meeting the same electrical and mechanical specifications. Tubes from a given vendor are interchangeable in all permanent magnets supplied by that vendor, although they are not interchangeable with magnets from other vendors.

Because 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 1966 and ended in August 1966, in an attempt to obtain information on tube life and equipment reliability as a function of operating level. Seven pairs of sectors (eight tubes per sector; i.e., 112 klystrons) were operated under substantially constant conditions of both beam voltage and repetition rate for 130,000 socket hours. The operating conditions, the average number of accumulated hours per socket during the endurance run, the number of klystron failures under the different operating conditions, and the average life at the time of failure are given in Table 10-5.

The number of failures experienced during this endurance run was so small that no meaningful statistical information was obtained. However, the fact that the number of failures was much higher in sector pair 5–6, running at maximum voltage and repetition rate, led to the conclusion that it would be desirable to limit the normal operating level to somewhat below 240 kV. During the first 6 months of 1967, one-half of the klystrons were nominally operated at 236 kV, the other half were nominally operated at 218 kV. To date there appears to be no significant difference in failure rate under these operating conditions.

Table 10-6 gives a summary of tube usage and failures since the beginning of operation. Although the mean age at failure is still low, it is predicted that the mean time to failure of klystrons will be in excess of 8000 hours at the present operating levels. This prediction is based on statistical analysis assuming a standard distribution of failure and a mean deviation equal to half of

Table 10-5 Klystron endurance run results

Sector pair	*Operating level*				*Average operating hours per socket*	*Cumu klyst failu*
	Reference voltage	*Klystron beam voltage*	*Klystron peak output power (MW)*	*Repetition rates*		
3/4	115	240–250	19–22	60	1175	1
5/6	115	240–250	19–22	360	1050	6
7/8	105	220–230	16–18	60	1200	—
9/10[a]	105	220–230	16–18	180	1140	—
13/14	105	220–230	16–18	360	1135	2
15/16	90	195–205	11–14	60	1200	1
17/18	90	195–205	11–14	360	1190	—

[a] This pair of sectors began the run approximately 60 hours after the others.

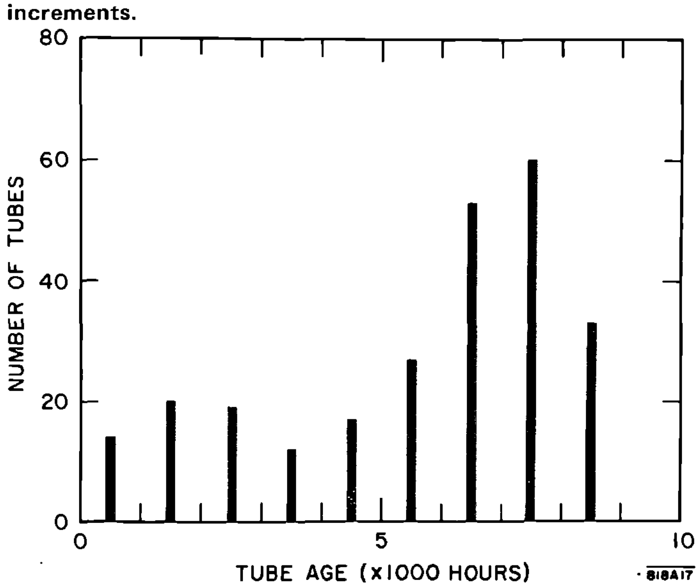
Table 10-6 Klystron usage and failure

	Operating hours		Failures			
			Quarter		Cumulative	
Dates	*Quarter*	*Cumulative*	*No.*	*Avg. life at failure (hours)*	*No.*	*Avg. life at failure (hours)*
To 13/31/65	—	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
To 6/30/67	301,000	988,000	26	2166	130	1130

the mean time to failure. This prediction has to be hedged by the fact that up until now only a small percentage of tubes have failed from old age, i.e., from such causes as lack of emission. Between one-fourth and one-third of the total failures were caused by output window failure, and at least one-third were caused by tube gassiness as evidenced by excessive arcing, pulse breakup, pulse droop, and/or oscillations. There were also a few failures caused by high-voltage seal punctures.

Another indication that the mean time to failure will probably exceed 8000 hours can be obtained from the plot of age distribution of tubes installed in the gallery (Fig. 10-16). This figure shows that the mean age on March 1, 1968, was 5600 hours, and the median age was 6200 hours.

Figure 10-16 Klystron age distribution (all vendors) in 1000-hour increments.



The good operating experience to date probably results not only from the high quality of the tubes procured and the quick-acting protection circuits installed, but also from the careful maintenance while the tubes are being installed in the accelerator. Further, it appears that the stringent specifications for SLAC klystrons have resulted in the high quality of the accepted tubes. For instance, the specifications on instabilities (phase and amplitude modulation) and faults probably result in rejection of any tube which would be marginally gassy.

In addition, a regular preventive maintenance program has been instigated in which each klystron receives a thorough check after every 500 hours of operation. Sometimes small instabilities are observed which can be eliminated by retuning the magnet. Sometimes a tube appears to be close to temperature-limited operation and an appropriate increase in heater power is introduced. In any case, the preventive maintenance is essential because the total instrumentation at each station in the gallery is minimal and it is essential for satisfactory operation of the accelerator that each klystron installed should operate within specifications.

In general, there have been few operational difficulties with klystrons. As noted above, the instrumentation on the machine is not as complete as might be desired for complete analysis of potential troubles. For this reason, many tube and pulse transformer tank assemblies are removed from the gallery for retest in the test laboratory. To date, the average number of tube removals is equal to twice the number of tube failures.

One of the main questions initially concerned the stability of the permanent magnets. At this time, there is no indication that the permanent magnets deteriorate in any way. Accordingly, it is felt that the total maintenance effort is greatly reduced by the use of permanent magnets compared to the conventional electromagnets and their power supply systems.

10-12 Extended operating life warranty (JVL)

When the klystrons were initially purchased from our vendors, they carried no warranty except for the guarantee of performance during the acceptance tests, including a 20-hour heat run at full power. The failed tubes were returned to vendors for repair. The vendor analyzed the tube and quoted a repair price based on the work to be done to the tube. The main disadvantage of the repair contract, from SLAC's standpoint, is the possibility of wide fluctuations in number of failures and, hence, in operating costs. In addition, there is no real incentive for the vendor to improve the life and quality of his products.

A modification of the initial procurement contracts has now introduced an extended warranty covering the tubes used at SLAC (in sockets on the accelerator). This extended warranty provides that all tube failures (except those caused by equipment malfunction or human error) will be replaced at no cost to SLAC. In return, SLAC makes a warranty payment for each operating hour of the tube on the accelerator. There are two hourly rates, a high initial rate and later a lower rate which continues until the tube fails. The rates have been negotiated so that the payments on the warranty would be about equal to those on the repair contract calculated on the basis of the mean time to failure expected at the time of the negotiations.

From an operational standpoint, the main advantage of the extended warranty is that a maximum hourly operating cost per socket is set by the terms of the agreement. In addition, at the end of the extended warranty period, all tubes initially contracted for will still be operable. With a repair contract, some tubes would be considered nonrepairable and the resulting attrition would considerably reduce the number of tubes available for operation.

Acknowledgments

The successful development of permanent-magnet-focused klystrons would not have been possible without the full cooperation of the members of the Klystron Department at SLAC and corresponding personnel of the vacuum tube companies having development contracts with SLAC in the early 1960's. Nor would the final machine performance have been possible without the cooperation of the klystron vendors who supplied the majority of the tubes being used on the machine.

Some members of the Klystron Department who have not been involved in the preparation of this chapter deserve special commendation for their outstanding contributions. First on the list should be G. K. Merdinian who not only designed the gun now used on the SLAC tube but was instrumental in the electrical and mechanical design of the window, as well as in the computations from which the major modifications of drift distances and improvement in efficiency resulted. The tube fabrication itself would not have been possible without the untiring efforts of J. P. Meloni. Tube testing has been principally the responsibility of R. L. Stringall. R. S. Callin has helped solve the mechanical handling problems and installation in the gallery, and T. Johnston has contributed greatly to the solution of operational and maintenance problems. K. Welch and B. G. Ryland by their continuing visits to tube manufacturers have helped maintain the flow of deliveries.

The window improvement work has been greatly assisted by the contributions of W. R. Fowkes (ring design), W. P. Schulz (sputtering techniques), and S. Sonkin (consultation on major problems).

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