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BREAKDOWN PHENOMENA IN HIGH POWER KLYSTRONS*

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ABSTRACT

In the course of developing new high peak power klystrons at SLAC, high electric fields in several regions of these devices have become an important source of vacuum breakdown phenomena. In addition, a renewed interest in breakdown phenomena for nanosecond pulse, multi-megavolt per centimeter fields has been sparked by recent R&D work in the area of gigawatt RF sources.

The most important regions of electrical breakdown are in the output cavity gap area, the RF ceramic windows, and the gun ceramic insulator.

The details of the observed breakdown in these regions, experiments performed to understand the phenomena and solutions found to alleviate the problems will be discussed.

Recently experiments have been performed on a new prototype R&D klystron. Peak electric fields across the output cavity gaps of this klystron exceed 2 MV/cm. The effect of peak field duration (i.e. pulse width) on the onset of breakdown have been measured. The pulse widths varied from tens of nanoseconds to microseconds. Results from these experiments will be presented.

The failure of ceramic RF windows due to multipactor and puncturing was an important problem to overcome in order that our high power klystrons would have a useful life expectancy. Consequently many studies and tests were made to understand and alleviate window breakdown phenomena. Some of the results in this area, especially the effects of surface coatings, window materials and processing techniques and their effects on breakdown will be discussed.

Another important source of klystron failure in the recent past at SLAC has been the puncturing of the high voltage ceramic insulator in the gun region. The breakdown phenomenon occurs in a region of apparent low electric field and low potential according to simulation studies (solutions to Laplace's equation) and occurs despite the deposition of a thin metallic coating on the inner vacuum surface. "Treeing" phenomena were also often present although not necessarily in the same region as the puncturing. A way of alleviating this problem has been found although the actual cause of the puncturing is not yet clear. The "practical" solution to this breakdown process will be described and a possible mechanism for the puncturing will be presented.

INTRODUCTION

Klystrons, and especially high power klystrons have the remarkable property that besides being useful sources of RF power also serve as a testbed for determining the electric standoff properties of various materials and geometric shapes. This paper describes some of our experience in the area of breakdown phenomena related to some of the more recent klystron designs at SLAC.

A klystron consists of several key components and regions which are subject to high levels of electrical stress. Figure 1 shows one of our latest production klystrons. It operates at a beam voltage of 350 kV and delivers 67 MW RF power. Its operating frequency is 2.856 GHz. The regions where breakdown phenomena have been a problem in this tube are the gun area, the ceramic window area and the output cavity area.

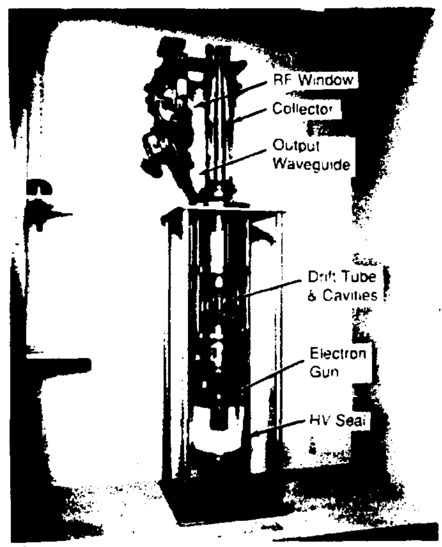

Fig. 1. The 67 MW production klystron.

The gun consists basically of a thermionic cathode, a focussing electrode (maintained at the same potential as the cathode) and an anode. The cathode is pulsed to a voltage of −350 kV. The pulse repetition rate is 180 times per second for pulse widths of 5.0 μsec. In order to maintain the voltage standoff between the cathode and anode a ceramic cylinder (or seal) connects the two structures.

The cavity and drift tube region serve to convert the unmodulated electron beam from the gun to a sharply bunched beam modulated at the input driving frequency. Each of the resonant cavities develop RF voltages across the cavity gaps (see Fig. 1). Beginning with the input cavity, which develops an RF voltage of approximately 2.5 kV, each of the succeeding cavities develop a higher and higher voltage due to the increasing RF beam

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modulation. At the output cavity the gap voltages reach a peak value of 420 kV. This corresponds to a peak surface electric field of 360 kV/cm. In some of the newer klystrons even higher fields are required for proper operation.

The output waveguide and window region directs the RF power generated at the output cavity to the external load which is, at SLAC, sections of a two-mile accelerator. Since the inside of a klystron must be maintained under a good vacuum at all times (typically 10^{-9} Torr or better) while at the same time permit RF power to reach the external load with minimal attenuation, a low-loss ceramic window is used. In the case of our latest production klystron we were forced to design a dual output window configuration because of the high peak RF fields and wide pulse widths involved.

BREAKDOWN PHENOMENA

High Voltage Seal Puncture

Approximately two-and-a-half years ago as the production rate of our klystrons reached a peak, a new failure mode began to appear in an alarming number of klystrons. The failure was an arc through the high voltage ceramic seal of the gun. Since the gun area of the klystron is maintained in an oil bath for voltage standoff any puncture of the seal not only destroyed the internal vacuum but coated the internal parts with oil. This meant that no parts could be reused. Initially it was assumed that the oil was contaminated with water. Testing indicated that indeed some of the failed tubes had oil contaminated with water. This problem was quickly brought under control but surprisingly the punctures continued to appear. Not only did the punctures continue but as the statistics improved it became apparent that the location of these punctures always occurred at the same axial location of the ceramic.

The geometry of the gun is shown in Fig. 2. The cathode and its support structure is located at the far right of the figure. The inner and outer anode corona rings are also shown with the ceramic seal sandwiched between them. An external cathode corona shield is also located at the base of the seal. To the right of the ceramic seal is the oil bath. The oil is tested to withstand an electric field strength of 150 kV/cm. The separation between the outer anode corona ring and the ceramic seal is 1.02 cm, and the separation between the inner anode corona ring and the seal is 0.32 cm. The location of the punctures was always at about the height of the outer anode corona ring. There was also evidence of arcing activity on the vacuum side of the seal opposite the inner corona ring but this did not appear correlated with the puncture sites.

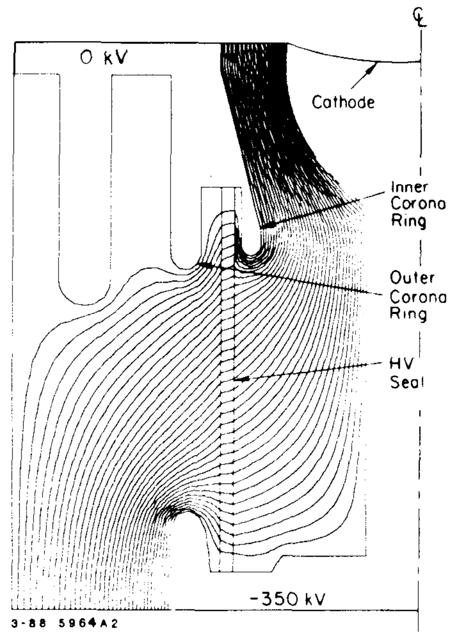

Fig. 2. Gun field profile with original geometry.

A series of studies was begun to investigate the electric field strength along the ceramic seal as well as the actual breakdown strength of the seal under actual pulsed conditions. In addition, since all high voltage seals which we use are coated with a TiN coating the properties of this coating were also studied.

In order to study the field strengths along the ceramic a series of computer simulations were performed using the program POISSON. Using this program the electrostatic problem could be solved for several boundary conditions using real values of the ceramic and oil dielectric constants. Two important ceramic boundary conditions were simulated. In one case the effect of the TiN coating was not included and in the other the coating was assumed uniform. Figure 2 shows the equipotential lines for the case of a uniform coating. Each equipotential line is separated from its neighbor by 10 kV. As can be seen from the figure the maximum potential between ceramic and outer anode corona ring is about 55 kV. This is insufficient for breakdown to occur. For the case of no TiN coating, the fields were reduced to only 20 kV. We also studied the standoff capability of the ceramic under normal pulsed conditions. A ceramic seal was place in a bath of oil with a negative high voltage electrode place against the inner surface of the seal. The grounding electrode was placed at different distances from the outer surface of the ceramic seal. For each distance the voltage was raised until punch-through occurred. The results are shown in Table 1.

As can be seen, (as long as the oil break-down limit is exceeded) the ceramic breakdown potential is independent of the ceramic seal to corona ring separation. From this one can draw the conclusion that the ceramic should not puncture even if the oil has a somewhat lower standoff capability than expected, since the point where the puncture occurs is much less (55 kV according to the simulation) than the measured breakdown level of 165-200 kV.

Table 1

Grounding Electrode Separation (cm)	Breakdown Voltage (kV)
0.5	165
0.25	190
0.0	170-200 (several tests)

Investigations were performed on the resistivity changes to the TiN coating as a function of temperature. It was thought that since the lower (towards the anode potential) portion of the ceramic seal was shielded from the radiant heat of the cathode support structure the coating might have a higher electrical resistivity than the rest of the surface. This would permit a higher than expected potential in the region of the puncture than expected. Results of measurements indicated that the resistance did drop a factor of two for each increase in temperature of 25 C. Unfortunately no sufficient temperature gradient could be found on the ceramic seal during actual operation to allow this effect to occur. Different types of conductive coatings were also found to have no effect on the puncture probability or location.

The results of our measurements indicate that for the expected potential distribution no punctures should occur. We are therefore led to the conclusion that the ceramic must acquire an excess charge density and (because the inner ceramic surface is coated) this excess charge must reside within the bulk of the ceramic material. A possible mechanism for this excess charge is by the emission of a small flow of charge from the cathode support structure to the ceramic. This could occur either by thermionic emission or (less likely) by field emission from the cathode support structure. This structure is quite hot (500 C) and most certainly would have a thin barium coating from initial cathode processing. Electrons which arrive at the ceramic surface near the corona ring would acquired a kinetic energy close to 350 keV. With this energy they would pass through the thin TiN coating and enter the bulk of the ceramic. (One can calculate the penetration of 350 keV electrons into aluminum oxide ceramic and find the mean depth to be approximately 0.026 cm). Once inside the bulk of the ceramic the charge would only slowly bleed off to ground since the bulk resistance is approximately $10^{+13}\Omega$ and the fields are roughly axial. In this way it is possible for a large accumulation of charge to build up within the ceramic and then bleed off slowly through the length of the ceramic or arc to the closest metallic surface. These metallic surfaces are the inner or outer corona rings. If this mechanism is correct then a solution to our puncture problems would be to shorten the outer corona ring. Any arcing that could take place would then only be to the inner corona ring. We therefore reduced the outer corona ring by 2.5 cm. Figure 3 shows the new design. After testing several klystrons to determine that no negative effects to the general performance resulted this change became the new design for all klystrons. Fifteen months and 125 klystrons later no klystron with this new design has had a punctured high voltage seal.

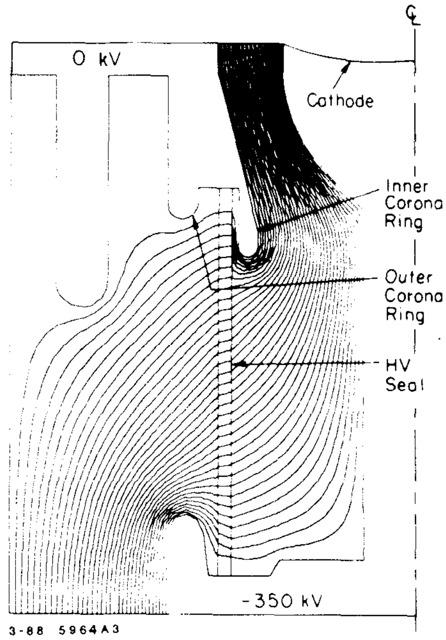

Fig. 3. Gun field profile with modified outer anode corona ring.

Window Failure

In high power klystrons, the RF ceramic windows are prone to several different types of breakdown phenomena because of the high levels of RF power they must transmit. Because of their susceptibility to failure, many studies and tests have been performed to ensure a window design with a high probability of long life. The ceramic window assembly is shown in Fig. 4. One may classify the main breakdown phenomena into three categories:

(a) *Dielectric failure.* This type of failure makes itself apparent by a puncture through the bulk of the window. It is caused by field gradients across the window which exceed the standoff capability of the material. Mechanisms for this type of breakdown will be described below.

(b) *Thermal failure.* This type of failure results from excessive differential heating of the window. It is evidenced by cracking (usually radial) due to thermal stresses.

(c) *Boundary failure.* This type of failure is caused by irregularities in the brazing interface resulting in thermal stresses along the periphery of the window at the copper/ceramic interface.

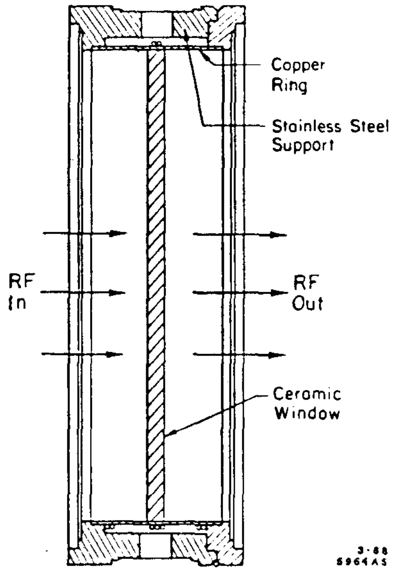

Fig. 4. Output ceramic window assembly.

Window Breakdown Mechanism

One of the principle mechanisms of dielectric failure results from the tendency of electrons within a waveguide to gain a net drift velocity in the direction of the Poynting vector of the RF fields. In klystrons this results in a flow of charge from the klystron toward the output window resulting in a buildup of negative charge on the upstream side of the window. On the other side of the window, however, a net positive charge results because of this same electron drift.

The resulting electric field across the window can become strong enough to exceed the dielectric strength of the ceramic resulting in a puncture. Impurities or voids within the window can enhance the chances of puncture by serving as breakdown centers.

Another phenomena which commonly causes windows to fail is single-surface multipactor. This phenomena usually takes place on the downstream side of the window because this side becomes positively charged more easily.

If an electron leaves the positively charged surface of a window (or any other nearby surface) it will be attracted back, towards the window surface. At the same time it can gain a great deal of kinetic energy from the transverse RF fields near the window surface. This gain in kinetic energy can be used to knock out secondary electrons from the surface. [Ceramics, such as aluminum oxide, have the property that their secondary electron yield is quite large (2.5-4.3).] If the transverse RF fields reverse direction in about the time it takes the secondary electrons to leave the surface of the ceramic and return, a rapid buildup of space charge can be built up around the ceramic surface and multipactor results.

A large portion of the kinetic energy gained by the electron from the RF fields is converted to heat energy on the ceramic surface. This heating can cause surface melting, pitting and eventually causes the window to crack. Arcing to nearby copper walls can also occur if the multipactor results in a localized pressure rise due to the melting ceramic or desorption of gases.

In order to alleviate the problems of multipactor and dielectric breakdown in our klystrons, several studies have been performed to assess the qualities of various ceramics and surface coatings.

The ceramics studied were sapphire, BeO, boron nitride, 95% alumina ($Al300$) and 99.5% alumina ($Al995$). The most promising materials from the standpoint of dielectric strength and resistance to cracking are BeO and alumina. Sapphire windows are exceedingly susceptible to cracking and boron nitride has too low a dielectric strength.

For our latest production klystron we use a pair of alumina windows exclusively, although we have in the past used BeO single windows. BeO is not used because of brazing difficulties and its inherent health hazards. However, it does have the important quality that it has the best thermal conductivity of all the ceramics tested.

In order to alleviate the problem of surface charge buildup as well as reduce the high secondary electron production yield (necessary for multipactor) various surface coatings have been tested. These coatings must be able to "bleed off" the surface electrons and have a secondary electron production coefficient ≤ 1. Not only is the material of the coating important but the thickness of the coating is also critical. Too thin a coating will result in it being inefficient while too thick a coating will result in excessive RF heating.

We have found TiN and chrome oxide coatings to work quite effectively when used in thicknesses of 25Å. For thickness much greater than 40Å, the windows become excessively hot.

To avoid klystron failures due to material imperfections (i.e., voids, inclusions), all windows are currently tested in a traveling wave resonant ring where they are subjected to twice the normal RF power levels before being installed in a klystron. This effectively identifies the mechanically weak or damaged windows early in production.

Besides thermal cracking due to excessive heating of the ceramic, windows can crack if the copper/ceramic braze fillet has voids or extends into the ceramic where it enters a higher RF field region. In both cases, boundary heating can crack the ceramic. Much effort has been expended in developing methods to ensure a uniform fillet at the boundary.

In an earlier window design used in the 5045, the RF electric field at the window was reduced by nearly 50% by altering the RF design so that the midplane of the ceramic was located at a voltage minima. This was accomplished by symmetrically locating inductive irises on each side of the window. This field reduction at the window, however, resulted in much higher fields elsewhere and a drastic narrowing of the passband. The resulting problems with field emission and dimensional tolerances moved us to abandon this approach.

Finally, we have found that even small amounts of dust or foreign particles on the ceramic surface can act as arc centers. While cleanliness and smoothness of window surfaces can be maintained during tube construction, it is much more difficult during actual klystron installation (and perhaps removal) in the accelerator gallery. We therefore made a change to the output design which has effectively eliminated window failures due to these foreign materials. We simply changed the output configuration so the windows are vertical instead of horizontal In this way any foreign material introduced into the output waveguide will deposit itself harmlessly in a low-field region of the waveguide.

INTERNAL ARCING

At SLAC we are currently investigating the feasibility of using high power X-band klystrons in future colliders. In these devices the cavity dimensions and cathode/anode spacings become quite small while the electric potentials, both RF and beam, remain the same or are greater. Table 2 indicates our experience so far with cathode/anode breakdown limits.

The first three tubes in Table 2 have run easily with the stated pulse widths and gradients.

Table 2. Anode/cathode peak field gradients.

Tube Type	Beam Voltage (kV)	Maximum Surface Gradient (kV/cm)	Comments
XK5	270	292	No breakdown with 3.5 μsec pulses
5045	350	201	No breakdown with 5 μsec pulses
150 MW	450	270	No breakdown with 1.8 μsec pulses
SL-3	330	303	Breakdown limited with 3.3 μsec pulses

With tube type SL-3, however, anode/cathode arcing has been a problem. Currently we have been able to run with a beam voltage of 350 kV after extended conditioning, but it appears that a limiting gradient in the gun region of a klystron is ~320 kV/cm for 1 μsec pulse widths. Part of the problem with this tube is due to the larger than normal focus electrode and anode surface, which increases the probability of breakdown.

We have also calculated peak fields in the output gap of several klystrons and for several modes of operation. Some of these results are listed in Table 3.

Table 3. Peak output gap field gradients.

Tube Type	Output Power (MW)	Maximum Surface Field at Output Gap (kV/cm)	Comments
5045	100	440	No breakdown at 2 μsec pulses
5045	67	360	No breakdown at 3.5 μsec pulses
150 MW	150	275	No breakdown at 1 μsec pulses
SL-3	10	808	No breakdown at 2 μsec pulses
SL-3	15	990	No breakdown at $> 0.7\,\mu$sec pulses
SL-3	17	1054	No breakdown at $> 0.6\,\mu$sec pulses

We see that for the first tube types operating at 2.856 GHz, no output gap breakdown is found for pulse widths of a few μsec. For tube type SL-3, we see that, because of the higher RF frequency (8.568 GHz) and smaller dimensions, the peak fields in the output gap become much higher for lower output RF power. An interesting point is that output gap breakdown for the SL-3 was observed for an output power of 15 MW for pulse widths $> 0.7\,\mu$sec and at 17 MW for pulse widths $> 0.6\,\mu$sec, indicating the pulse width dependence of breakdown.

In collaboration with Lawrence Livermore National Laboratory (LLNL) this tube type, SL-3, was also run using their induction linac as a high energy, high current source. We were able to measure output power levels corresponding to fields of 2.2 MV/cm for pulse widths of $\simeq$30 nsec. No breakdown was observed.

A plot of the results of the SL-3 measurements showing the importance of pulse width in standing off high electric field gradients is seen in Fig. 5.

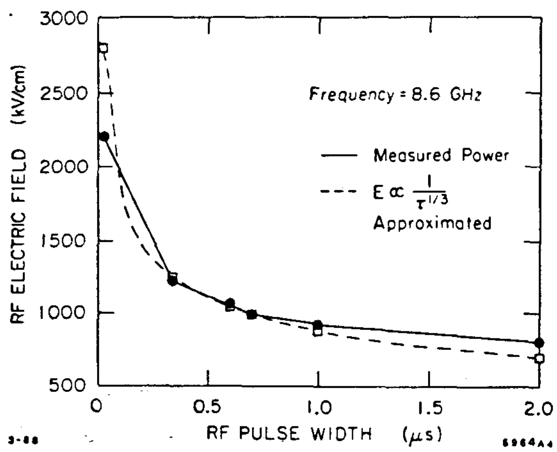

Fig. 5. Electric fields in the output gap of SL-3.

SUMMARY

The development of high power klystrons at SLAC has been contingent on finding solutions to high voltage breakdown problems. Three major areas which have been studied are high voltage ceramic seal punctures, window failures and arcing across the output and cathode/anode gaps.

A solution to the ceramic seal puncture has been found and a possible mechanism has been suggested. Efforts are continuing into ways of better understanding this breakdown phenomena.

Considerable research has gone into developing long-lived RF windows. These studies have involved experimentation into materials, surface coatings and processing techniques. Alternate window geometries have also been tried. As a result of these studies, the current RF window design has been shown to be quite resistant to breakdown.

As part of our R&D efforts in developing higher power klystrons, we are finding apparent breakdown limits in cavities and in gun designs. We have found these limits to be pulse-width dependent. Further studies into ways of raising these breakdown limits are an integral part of our overall R&D effort.

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