25 YEAR PERFORMANCE REVIEW OF THE SLAC 5045 S-BAND KLYSTRON*

Aaron Jensen[#], Arthur Scott Beebe, Michael Fazio, Andy Haase, Erik Jongewaard, Chris Pearson, Daryl Sprehn, Arnold Vlieks, Larry Whicker, SLAC, Menlo Park, CA 94025, U.S.A.

Abstract

The SLAC 5045 S-band klystron has proven to be a remarkably reliable high peak power tube. Originally developed in the 1980's as an upgraded RF power source for the Stanford Linear Collider, it has continually powered the SLAC linac in support of numerous programs in particle physics and photon science. The large number of tubes built and operated (more than 800) coupled with accumulated running statistics over the last 25+ years represents an unprecedented wealth of operational experience for high pulse power klystrons in accelerator applications. Mean time between failures has continued to rise during this period and is frequently in excess of 100,000 hours during the last several years. Lifetime statistics as well as some important failure modes are presented and examined here.

INTRODUCTION

SLAC National Accelerator Laboratory has continuously operated its 2-mile accelerator, which utilizes a complement of 245 klystrons, for more than 40 years. During this time a wealth of data has been collected.

In 1987 preliminary runtime data and failure modes were published [1] for the 5045. However the tube has matured significantly since then and much more data is available for analysis.

INTRODUCTION OF THE 5045

In 1987 the 5045 klystron had recently replaced the XK5 klystron as the linac's primary RF source. At the time there were concerns a higher power klystron would not achieve a Mean Time Between Failure (MTBF) comparable with the XK5. However, after resolving several infant mortality failure modes, the cumulative MTBF of the 5045 has surpassed the XK5 and continues to improve (the cumulative MTBF is defined as the total accumulated high voltage hours on all klystrons since the beginning of time divided by the [total number of failed klystrons since the beginning of time plus 50% of klystrons in evaluation at the time]).

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#aaron@slac.stanford.edu

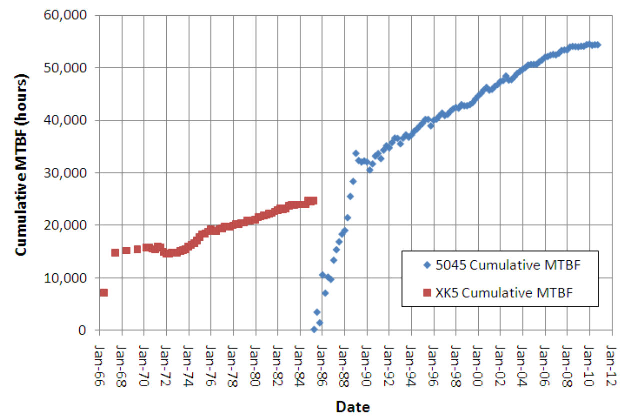

Figure 1: Cumulative MTBF for the 5045 and XK5 Klystrons.

5045 SPECIFICATIONS

The 5045 klystron is the primary RF source used at SLAC National Accelerator Laboratory. The name 5045 is derived from the tube's original specifications of 50MW peak output power and 45kW average output power. The tube presently operates nominally at the higher peak output power of 65MW with a shorter 3.5 μs pulse width (originally 5 μs). Other operating data for the 5045 are shown below in Table 1.

Table 1: Typical 5045 Operating Parameters

Operating Parameter	Value
Frequency	2.856 GHz
Beam Voltage	350 kV
Perveance	2.0 $\mu A/V^{1.5}$
Peak Output Power	65 MW
Average Output Power	41 kW
RF Pulse Width	3.5 μs
Pulse Rep. Rate	180 Hz
Gain	50 dB
3 dB Bandwidth	20 MHz
Saturated Efficiency	45%
Cathode Current Density	8 A/cm^2

Figure 2. 5045 Klystron.

5045 OPERATING STATISTICS

Over 800 tubes have been built and operated at SLAC. Although, it is difficult to analyze the accumulated data completely, it is easy to make general observations about tube lifetime and typical failure modes.

Metrics relevant to the discussion of 5045 reliability include:

Average Age of On-Line Klystrons: total accumulated high voltage hours to date of the 245 installed 5045 klystrons.

12 Month Age of Failed Klystrons: total accumulated high voltage hours for all 5045 klystrons failed during the previous 12 months divided by the number of failed klystrons during the same period.

12 Month Average MTBF: total high voltage 5045 klystron hours accumulated on all klystrons during the previous 12 months divided by the total number of failed klystrons during the same period.

Plots for these values are shown in Figure 3.

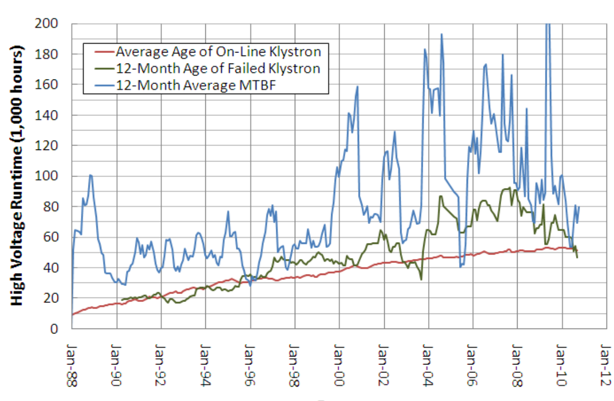

Figure 3: 5045 Runtime Statistics.

The average age of klystrons in the gallery has surpassed 50,000 high voltage hours. Many tubes have even surpassed 100,000 hours. The distribution of cumulative high voltage hours is shown if Figure 4. The black bars represent hours accumulated by klystrons when they failed. The large numbers of early failures are associated with infant mortality failure modes such as mechanical defects and tubes failed in the mid 80's for failure modes that have since been eliminated through engineering. The on-line klystron hours are shown in turquoise and show a much more even distribution of hours. However, the number of accumulated high voltage hours appears to drop off rapidly much above 90,000 hours.

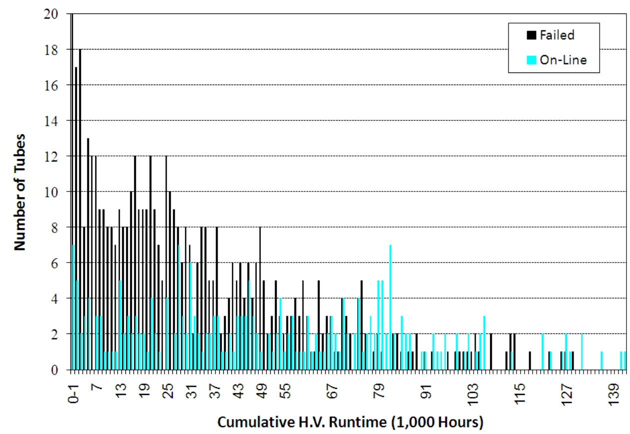

Figure 4: 5045 Cumulative High Voltage Runtime Hours.

Another metric of interest is the manufacturing yield, which is the percentage of manufactured klystrons that are put into service. The yield shown in Figure 5 has behaviour similar to the cumulative high voltage runtime. The yield was low when 5045s were first being built but after an initial learning curve the yield increased significantly. The yield also tends to improve slightly during higher production and decline during lower production (such as after 2005), a phenomenon typical in manufacturing.

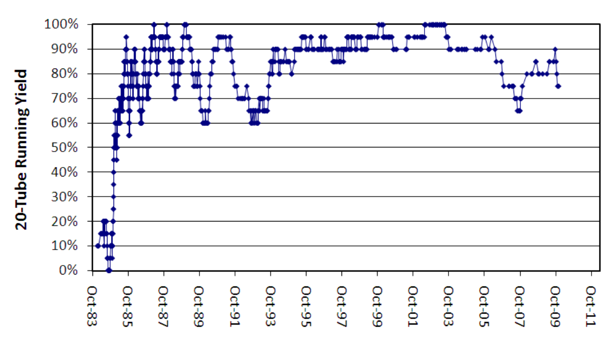

Figure 5: 5045 Manufacturing Yield.

5045 FAILURE MODE STATISTICS

All tubes eventually fail, at which point they must be repaired or scrapped. SLAC defines a 5045 tube failure as any tube that requires breaking vacuum for repair. This would not include failures such as water leaks, magnet shorts or other exterior failures.

Once a tube has been diagnosed in the klystron test lab as a failure, it is refurbished, if possible. In this case several components are replaced such as the gun and windows. SLAC tubes are typically refurbished three to four times and a letter code attached to the serial number to indicate how many times the rf output structure has been recycled.

The reasons for tube failures are shown in Figure 6. To be completely accurate this graph should be generated after the tube has been opened and autopsied. However, the data is not as readily available and will be presented at a later date.

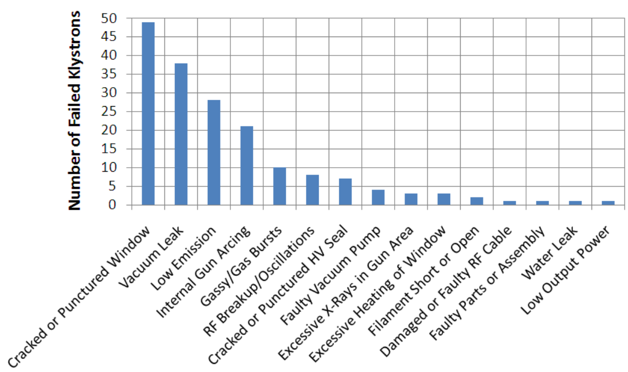

Figure 6: Reasons for 5045 Failure Since ~1993 as Determined Prior to Tube Autopsy.

The graphs show certain failure modes are more common than others. Cracked or punctured windows are the dominant failure mode. Low emission, internal gun arcing, and gas bursts are also common failure modes and are likely the precursor to an end of life cathode. However, determining the exact root cause of failures is often difficult.

The lifetime of tubes failed in the last five years for end of life cathode symptoms are shown in Figure 7. Many of the failed tubes had lifetimes of 60,000 to 100,000 high voltage hours but tended to fail more often between 20,000 and 40,000 hours. A further study including tubes over a longer history is planned. It would also be of interest to correlate the lifetime with heater current.

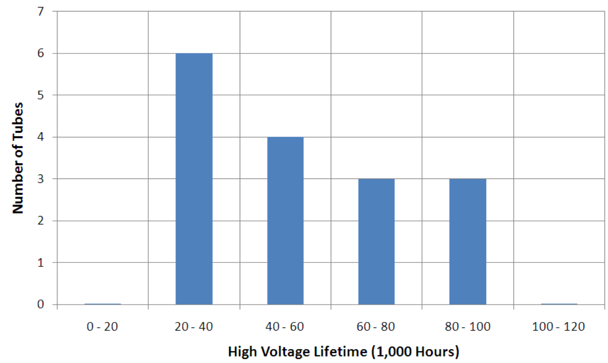

Figure 7: Lifetime of Tubes Failed for an End of Life Cathode During the Last 5 Years.

Cracked or punctured windows are a primary failure mode for the 5045. To further evaluate the failure, the number of tubes with window failures is plotted against high voltage runtime. Interestingly, 5045 window failures have a strong Gaussian distribution centered around 58,000 high voltage hours. Window development is currently an area of research which may lead to extended lifetimes for future tubes.

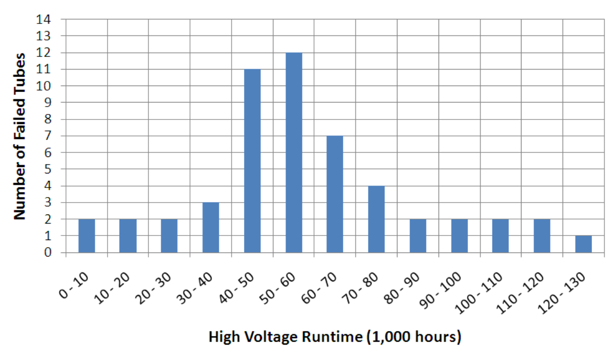

Figure 8: Lifetime of Tubes Failed for Leaky or Broken Windows Since ~1993.

SUMMARY

The 5045 klystron has been operating over 25 years at SLAC National Accelerator Laboratory. It is approaching statistical maturity and provides a wealth of data with respect to tube lifetime and failure modes.

The most common failures are associated with windows and failures likely related to an end of life cathode. Further investigation of window failures is underway.

The 5045 has become a very successful RF source for the linear accelerator. The average age of online klystrons in the gallery is over 50,000 high voltage hours and continues to rise.

REFERENCES

[1] M. A. Allen et al., Performance of the SLAC Linear Collider Klystrons, SLAC-PUB-4262, March, 1987.