PERFORMANCE OF THE SLAC LINEAR COLLIDER KLYSTRONS*

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1. Summary

There are now 200 new, high power 5045 klystrons installed on the two-mile Stanford Linear Accelerator. Peak power per klystron averages over 63 MW. Average energy contribution is above 240 MeV per station. Electron beam energy has been measured as high as 53 GeV. Energy instability due to klystron malfunction is less than 0.2%. The installed klystrons have logged over one million operating hours with close to 20,000 klystron hours cumulative operating time between failures. Data is being accumulated on klystron operation and failure modes with failure signatures starting to become apparent. To date, no wholesale failure modes have surfaced that would impair the SLAC Linear Collider (SLC) program.

2. Klystron Station Design

The present specifications for a 5045 are as follows:

Operating frequency	2856 MHz
Number of cavities	6
Beam voltage	350 kV
Beam current	414 A
Microperveance	2.0
Output power (peak)	67 MW
RF pulse width	3.5 μsec
PRF	180 pps
Efficiency	46%
Gain	53 dB
Cathode current density	8A/cm^2
Cathode type	dispenser

In order to carry out the planned experimental program at the SLC interaction region, the accelerator must deliver over 50 GeV electron beam energy. An energy upgrade effort was started as part of the SLC development program that involved the rebuilding of all klystron modulators, the design and installation of a new interlock and diagnostic system for the klystron stations, and the development of a new, higher power, longer pulse width klystron design named the 5045. A description of the klystron, modulator, pulse tank, interlock, and diagnostic system is given elsewhere.[1] This report covers system operating experience in the last year.

3. Klystron Performance, Faults, and Failure Analysis

Installation of 5045-type klystrons in the gallery started in the summer of 1985. Today, 200 5045 klystrons are in place and operating satisfactorily. Production of 5045 klystrons is continuing at the rate of 14 starts per month, and recently, most of this production has successfully completed initial run-up testing and been accepted for gallery use. The production yield is over 75%.

As of March 1987, the total running time of 5045 klystrons in the gallery is over one million hours. During this period, there were 56 klystron failures Many of these failures occurred in tubes assembled before present manufacturing improvements were implemented. This amounts to 18,800 mean hours between failure for the installed klystron complement. The average peak power delivered by each klystron is above 63 MW with new production tubes delivering above 65 MW. This has yielded an average beam energy contribution of 240 MeV per standard klystron station. When all optimizations of timing, power, phase, etc. are completed, 250 MeV per station is expected. Recently, 2×10^{10} electrons in a single bunch were accelerated to 53 GeV.

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Klystron failures that have necessitated removal are in the following catagories:

Window failures

These account for about one third of all gallery failures. In spite of the best efforts to keep the windows free of foreign matter, most window failures show evidence of some material on the window that caused arcing, pitting, and eventual fracture. The windows in the early klystrons were horizontal. It was simple to manufacture that way, and the windows could be easily inspected. Unfortunately, it was easy for material to fall on the windows during tube installation, and also later during operation from deposit flakes in the old waveguide system. The klystron output waveguide system was redesigned to allow windows to be vertical, and the window faulting problem has virtually disappeared. Since it is uneconomic to remanufacture early production klystrons to the vertical window format, extreme care is taken when installing and handling output waveguide components, and every window is 'borescoped', (the condition recorded on video tape), during any removal or installation operation.

High voltage seal puncture

This was a potentially serious problem that was recognized only later in production. The symptom was that an operating klystron would suddenly experience internal arcing coincident with a rapid rise in tube pressure. The degree of pressure rise varied, but when the tube high voltage seal was inspected, an arc puncture was observed immediately adjacent to the location of the internal and external ground side corona rings. A Poisson plot of the electric fields in the region showed no unusual stress, and a transient numerical solution of a cathode-anode arc yielded similar negative results. Attention was drawn to the internal charge bleed-off coating on the ceramic bushing. The resistance was suppose to be multi-megohm, but some coatings were observed to be in the sub-megohm range with a high negative temperature coefficient. With this condition, it was possible to develop a very high negative potential from a point on the coating to the internal ground shield electrode, and also through the ceramic to the external ground shield electrode. Careful autopsy inspection showed evidence of discharges from the internal ground shield to the ceramic, and seal punctures occurred almost exclusively between this point and the external ground shield electrode. The decision was made to cut back the external corona shield electrode on all magnet-tank assemblies in current production, and to cut back internal ground electrodes in half of the new production tubes as an experiment. Since those decisions, there have been no punctures of high voltage ceramics with altered corona shields. There is a plan to re-fit early production tubes in the gallery with modified magnets to prevent further seal punctures.

Regenerative instability, low power output, RF output gap breakup

Some of these symptoms are related to the klystron beam quality, and to the tune of the microwave interaction cavities. It was found early in production that tubes that were unstable in the space charge-limited-beam-regime could be made stable by running the cathodes temperature limited at some reduction in klystron perveance but not necessarily power output. Many beam and RF cavity studies were undertaken, and designs were altered to minimize instability and increase power output. RF output gap breakup is a symptom of beam scraping damage. Instability and RF output gap breakup have not been completely eliminated from current production tubes, but most new tubes

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can be made to operate stably with output power above 65 MW with minor focus coil adjustments.

Gassy cathodes

The manufacturing process of dispenser cathodes involves the use of polystyrene in the sintered tungsten matrix. This must be completely removed by careful firing before the cathode is impregnated. If any carbon trace remains, the cathode becomes a permanent source of CO that raises tube pressure as a function of cathode temperature. Great care is taken in cathode inspection and processing, but still, some gassy cathodes make it into production tubes. The number of these gassy cathodes is going down with more rigorous cathode processing, and even tubes with gassy cathodes whose pressure does not exceed 1×10^{-7} torr still give good service.

Mechanical, water, and pulse tank problems

Systematic weaknesses were carefully studied, redesigns undertaken, and the current production seems to be largely defect free. The re-fit program will incorporate all these changes into gallery klystron-tank assemblies.

Cathode lifetime

The usual lifetime of electron beam devices is ultimately determined by electron emission from the device cathode. The new 5045 klystrons use dispenser cathodes which are known to have very long life because of the dispenser nature of the surface, and the lower cathode operating temperature, 950°C. Some of the 5045 klystrons have accumulated over 10,000 hours of cathode heating. Calibration of early data is imprecise, but based on the data available, it is estimated that these klystrons will average over 40,000 hours of useful cathode life.

4. Klystron Control and Diagnostics

Operating parameters of each klystron station in the linac are monitored by the SLC VAX computer system. Klystron RF drive, pulse timing, and RF phase are under computer control.[2] The computer controlled Phase and Amplitude Detector (PAD) and the Modulator Klystron Support Unit (MKSU) both have wave shape data sampling capability that allows inspection of klystron beam and detected RF wave shapes at any graphics terminal. A number of control and analysis sub-routines are resident in the VAX for analyzing wave shapes and setting parameters. An example is the klystron drive saturation program. When the routine is called into action at a klystron station, the klystron RF drive is programmed in increments from zero to maximum drive. The klystron output is recorded at each increment, and the saturation curve is displayed. The peak of the klystron output is found and indicated on the display, and if the operator is satisfied with the setting found, a push of an acceptance button sets in this optimum drive value. This same control feature can be used in another sub-routine to use a klystron as a beam energy vernier.[3]

The SLC makes use of the SLED energy doubler system in which the RF energy in the 3.5 μsec RF pulse is stored in an RF cavity set for 2.7 μsec, and then by means of a 180° phase change in the klystron RF drive, is delivered as a high peak RF pulse to the accelerator guide. The detected RF wave shape of this pulse is shown in Fig. 1 as seen on the sampled data display of the PAD.

The whole RF coupling system is carefully calibrated so that these displays are scaled directly in MeV contribution to the beam, or peak klystron power as scaling dictates. This figure demonstrates another analysis sub-routine in action. The RF waveshape is analyzed, the accelerator filling portion of the wave shape is fitted to a trapezoid, and the energy contribution that this trapezoid of RF power contributes to the beam is calculated. The vertical line corresponds to beam time in the center of the accelerator guide. The wave shape shown is taken at a properly timed, correctly tuned station. Secondary diagnostics looks at the wave shape and timing, and flags stations that are out of specification.

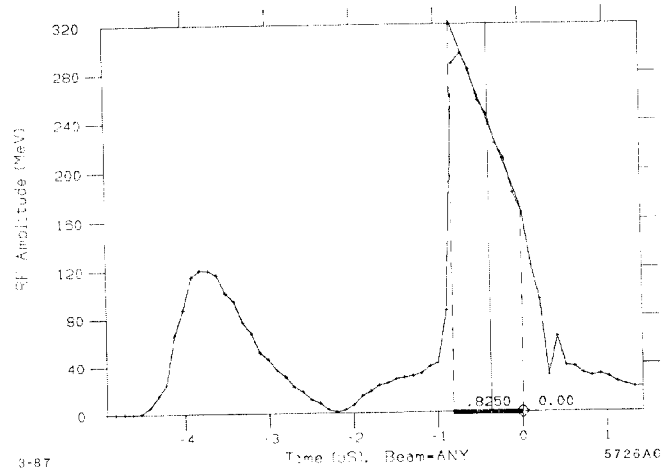

Fig. 1. SLED RF wave shape.

The klystron beam voltage and beam current pulses are also available on the sampled displays. From these plots, klystron perveance is derived. Figure 2 shows a typical beam voltage plot. Both pulse flatness and pulse width are important in generating the required RF pulses. Another sub-routine analyzes this display, finds the usable portion of the beam pulse as shown, then checks the flatness, pulse width, and timing to insure maximum energy contribution of the station.

The final station parameter that determines station energy contribution is the phase of the RF with respect to the beam. The correct phase is determined with the use of the beam itself. Once established it is continuously measured by a phase detector and held within a few degrees over long periods of time by the computer.

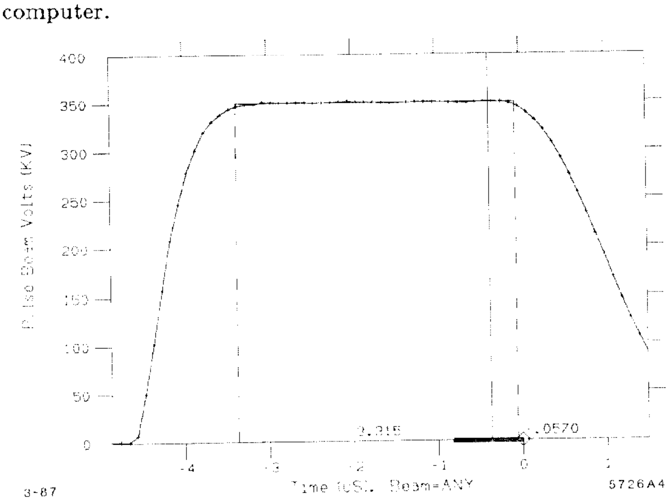

Fig. 2. Klystron beam voltage pulse.

The maximum energy phase for each klystron is found with an energy spectrometer looking at the beam at the end of the linac. Until recently, beam orbit uncertainty and energy resolution of switchyard energy analysis equipment did not permit accurate phasing of individual klystrons. The new SLC beam transport and instrumentation system now allows accurate energy analysis. Still another sub-routine has been written that collects many energy points as a function of a klystron station phase shifter, statistically processes the data, fits a sine wave to the resulting plot, and determines the correct phase setting for maximum energy contribution of the klystron.[3] Figure 3 shows a plot of this sub-routine in action. This system can set klystron phases to within 2° of maximum energy contribution.

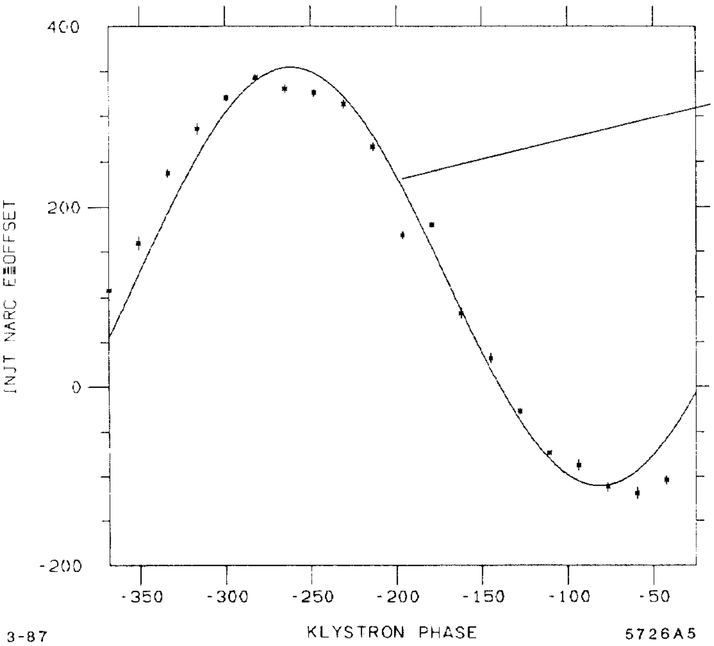

Fig. 3. Klystron phase-energy analysis.

The energy analysis system uses several beam position monitors before and after the beam splitter dipole near the beginning of the arcs. The energy is measured as a beam position after the bend where the design dispersion is 70 mm. Position information obtained from before the bend is used to remove trajectory errors from the energy measurement. The single reading resolution in energy is 0.06%.

This same energy analysis system is useful in determining the overall energy stability of the klystron complex. Klystrons with phase jitter, or intermittent RF breakup contribute energy instability to the beam. The energy is sampled on every beam pulse, and a pulse-by-pulse feedback system has been built to remove systematic changes.[4] The feedback system records the energy on each pulse. Two data samples of 900 beam pulses each were taken at 47 GeV and 5 pps without the energy feedback on and are displayed in Fig. 4 and Fig. 5.

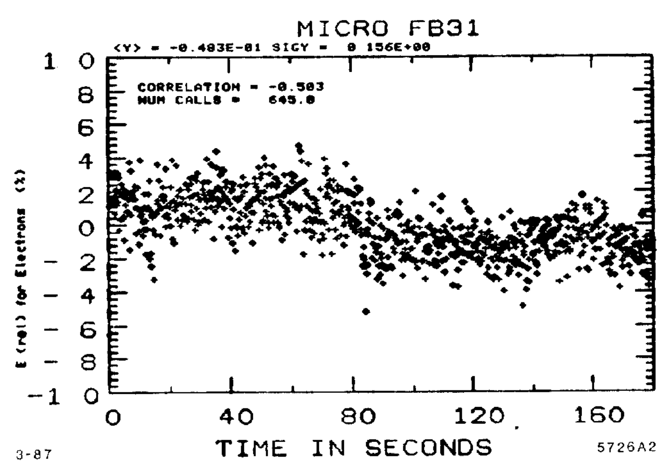

Fig. 4. Energy plot with phase jitter.

Figure 4 shows a jittery beam caused by several intermittent klystrons. Figure 5 shows the beam a few minutes later with those tubes taken off the beam. Fig. 5 resembles most closely typical operation. Pulses with high energy tend to be associated with low beam currents (less beam loading).

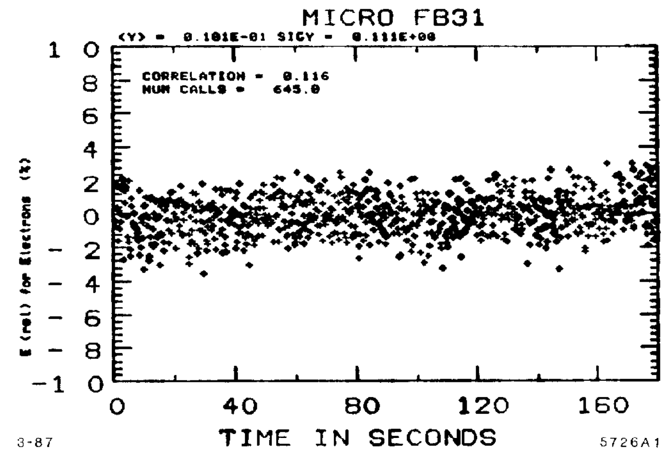

Fig. 5. Typical stable energy plot

Data points with low energy tend to have missing, or partially missing klystron pulses. Large energy losses ($\approx 0.87\%$) are caused by missing triggers which affect several klystrons at a time. The RMS energy error of the data in Fig. 5 is 0.13%.

Table I. Missing Energy Pulses per 10,000 Beam Pulses

Missing trigger	25
Klystron cycles	50
Energy offset (steps)	100
Single klystron faults	120
Sub-booster trip	50
Total	345

An estimate of the missing energy pulses (outside 3σ), is summarized in Table I. It is assumed that a modest ten pulse average feedback system is in operation. The estimated total missing pulses is 3.5%.

5. Implication for Future Linear Colliders

The performance of the SLC klystrons is very encouraging for future large linear colliders. The demonstrated inherent stability of the klystrons, together with its microprocessor control phase and amplitude detectors and control software, makes feasible operation of the thousands of klystrons necessary for the next generation colliders. The 3.5% missing energy pulses can be significantly reduced as klystron performance improves. A 10% specification for a linear collider is contemplated and this is now feasible with an order of magnitude increase in the number of klystrons over that now in use in SLC. Also, the much shorter pulse widths ($\approx$100 nsec) required for linear colliders will also lead to improved klystron performance. The prospects for using klystrons in large linear colliders appear to be very good.

References

1. Operational Experience with SLAC Energy Upgrade by M. A. Allen, et al., SLAC-PUB-3941 April 1986.
2. Computer Control of RF at SLAC by H. D. Schwarz, IEEE NS-32, No. 5, 1847 (1985).
3. Computer Control of the Energy Output of a Klystron in the SLC, by R. K. Jobe, et al., Proceedings of this conference.
4. Fast Energy and Energy Spectrum Feedback in the SLC Linac, G. Abrams, et al, Proceedings of this conference.