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Performance of a 150-MW S-Band Klystron[1]

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Abstract. As part of an international collaboration, the Stanford Linear Accelerator Center (SLAC) klystron group has designed, fabricated, and tested a 60-Hz, 3-μs, 150-MW S-band klystron built for Deutsches Elektronen Synchrotron (DESY). A test diode with a 535-kV, 700-A electron beam was constructed to verify the gun operation. The first klystron was built and successfully met design specifications. The 375-MW electron beam represents a new record for SLAC accelerator klystrons in terms of voltage, current, energy, and ruggedness of design The rf output power is a 150% increase over the S-band tubes currently used in the two-mile-long linear accelerator at SLAC. This paper discusses design issues and experimental results of the diode and klystron.

INTRODUCTION

The Stanford Linear Accelerator Center (SLAC) klystron group is currently designing, fabricating, and testing high power klystrons which range from 477-MHz to 11.424-GHz, and from 1-MW under continuous operation to 150-MW at 3-μs pulsewidth. These klystrons power accelerators which are either operating, under construction, or will be used as test accelerators to study advanced concepts for future collider development.

The linear collider at SLAC uses S-band klystrons operating at 60-MW peak output power. Due to the experience with constructing and operating hundreds of these tubes (known as 5045 klystrons) it was decided to limit design parameters, such as gradients and cathode loading, to at or below the levels of the 5045. Due to the high power requirement of the 150-MW klystrons, the cathode current, gun convergence, beam current density and voltage, focusing field, pulse energy, and the power in the output cavity will be significantly higher than in a 5045. Some important design parameters are shown in Table 1.

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TABLE 1. Design parameters for the 150-MW klystron.

Beam voltage	535-kV
Beam current	700-A
RF Pulsewidth @ rep rate	3-μs @ 60-Hz
Cathode loading	2:1 (6-A/cm^2 max)
Cathode convergence	40:1 (5.25" dia.)
RF output power	150-MW
Saturated gain	~ 55-dB
Efficiency	≥ 40%
Operating frequency	2998-MHz
Solenoidal focusing field	2100-gauss

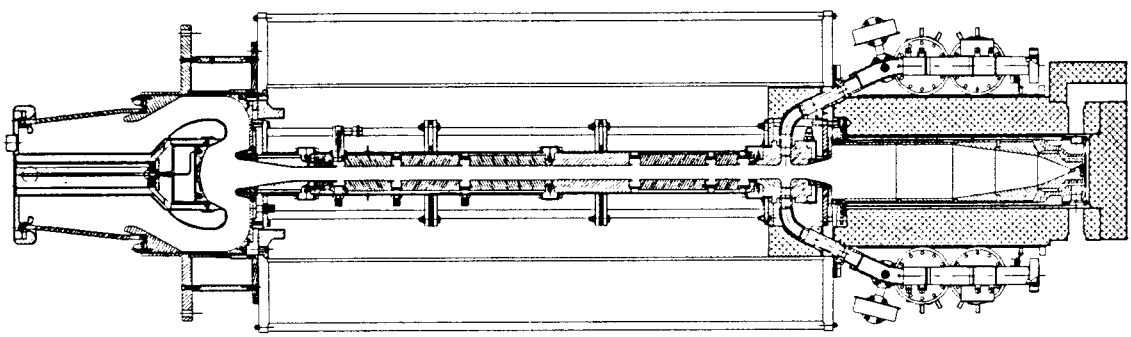

FIGURE 1. The 150-MW klystron assembly shown with magnets and lead.

The completed klystron stands 104 inches tall from the gun baseplate to the collector tip and weighs approximately 600 pounds. The klystron is inserted into a 15-kW solenoid and dressed with 3 to 4 inches of lead (Fig. 1).

DESIGN

With 40% efficiency desired, the 150-MW klystron required a 375-MW electron gun. A diode was first constructed to verify the gun operation. At 3-μs operation the diode was processed to 500-kV when rf gun oscillations were detected. Despite the oscillations, the diode was operated for short periods of time at full power with 3-μs pulsewidth and 60-Hz, and up to 550-kV at slightly shorter pulsewidths. The microperveance was measured at 1.78 with 99.8% beam transmission, which agreed well with design.

After discovery of the diode rf gun oscillation, two changes were made to the klystron gun design. The gap suspected of coupling the 1.365-GHz oscillation to the beam was shorted, and small strips of molybdenum were fabricated to short out another possible source of oscillation at the cathode heat shield gap. With these two exceptions, the klystron gun was copied directly from the diode.

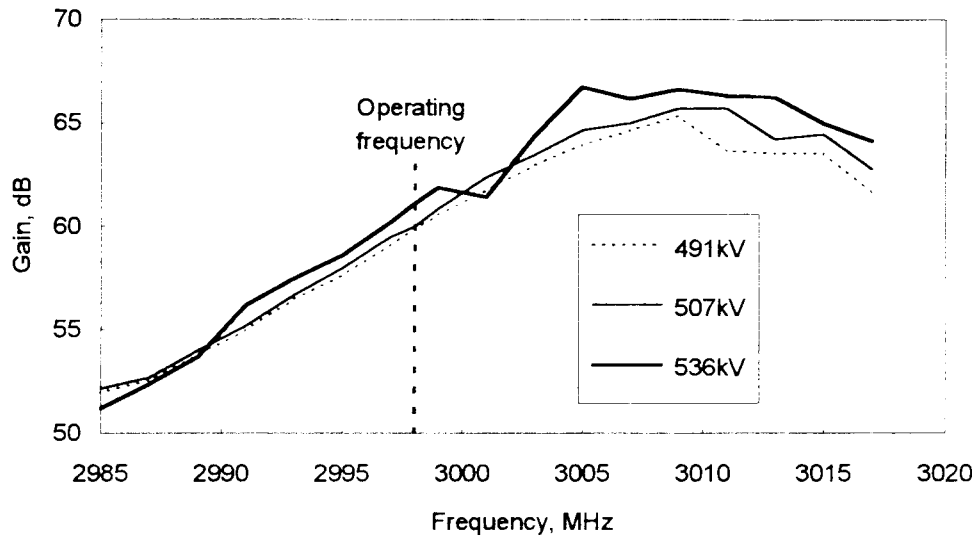

FIGURE 2. Small signal gain of the 150-MW klystron verses frequency.

KLYSTRON EXPERIMENTAL RESULTS

The small signal gain is slightly higher at 3.01-GHz regardless of beam voltage settings (Fig. 2). Large signal data was not taken across such a wide frequency band. It was found that as the tube approached saturation, the optimum frequency appeared to drop. At 150-MW, the optimum frequency had fallen to 3.002-GHz, and the saturated gain was approximately 54-dB.

While operating at 3-μs and certain combinations of magnetic field and beam voltage, an rf oscillation would appear at the falling edge of the beam pulse which, if not checked by adjusting the magnetic field, lead to beam interception and gas formation. The frequencies of the oscillation were found to be 8.588-GHz and the second harmonic at 17.18-GHz. Areas of oscillation are plotted which show measured edges of oscillation-free operation in solid tic marks (Fig. 3). The "cones" which expand upward and to the right are areas at which the oscillation occurred, weaker at the edges of the cones and stronger in the centers.

Theories concerning the rf oscillation mechanism must include the periodicity with magnetic field and the frequency stability. One possibility is that a slightly off-axis beam is kicked further by an asymmetric mode in one cavity and spins around a certain number of times until it reaches the next cavity capable of being exited by an off-axis beam at approximately the same frequency. The signal feeds back to the first excited cavity via the drift tube and if enough time and gain are

present, an oscillation builds up. As the magnetic field is increased, the beam spins around more, and soon the two cavities are no longer in a (azimuthal) phase relation which is synchronous. When the magnetic field is increased enough, the beam has spun around one extra revolution and the cavities are again in phase and the oscillation can again occur. Despite the mechanism, stable operation of the klystron requires keeping the operating parameters within a safe "channel" between the oscillation cones.

Klystron performance indicated that the tube was capable of more than 150-MW. The rf output power versus rf input power clearly shows that operation

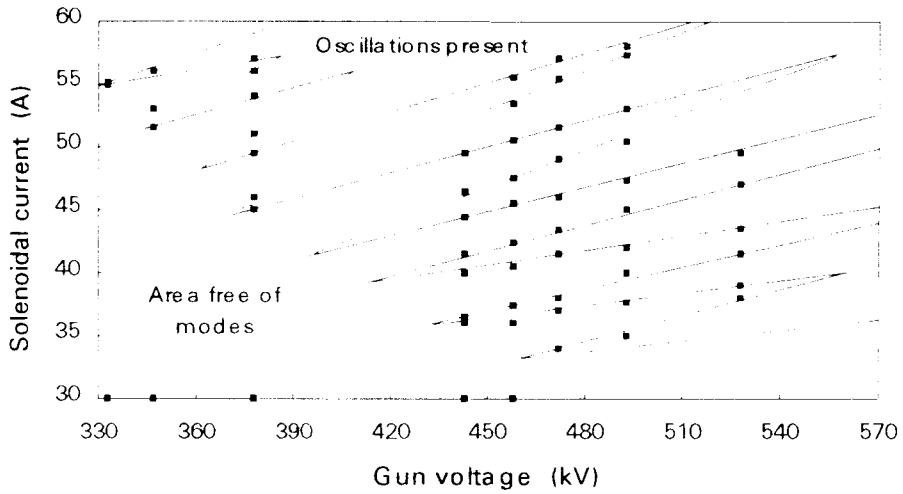

FIGURE 3. Area of klystron self-oscillation at 3 μs operation. Coil current of 45-A corresponds to an 1800 gauss axial field.

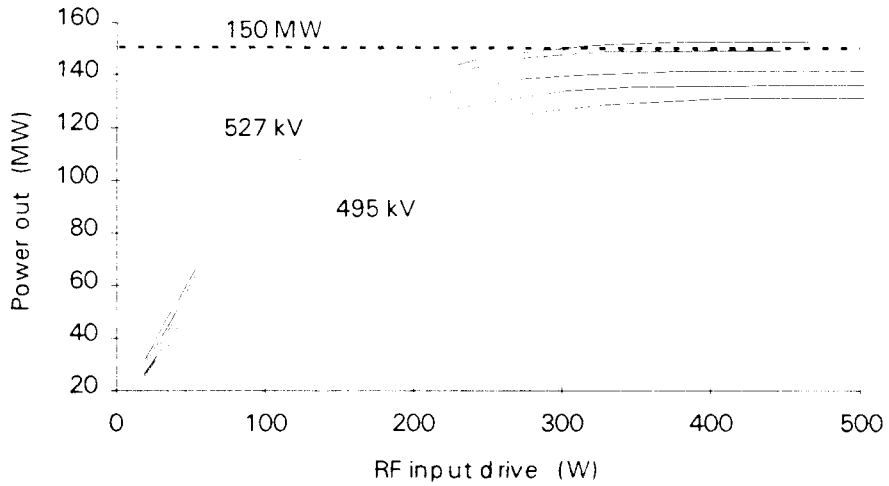

FIGURE 4. Measured output power versus drive of the 150-MW klystron at 527, 523, 511, 503, and 495-kV (μK=1.8, Bz=1800-g, τ=3-μs, Rep rate=60-Hz).

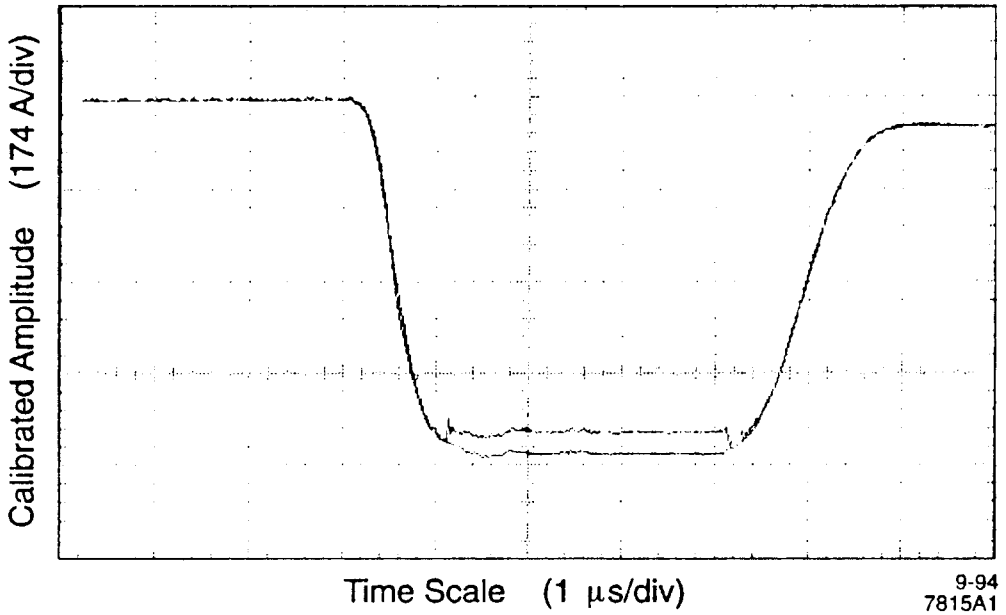

FIGURE 5. Typical collector current waveforms with rf on and off (150-MW, 3-μs, 60-Hz, 1800 gauss).

beyond 150-MW is possible (Fig. 4). Calorimetric data, collector and gun current, pulse transformer primary and secondary voltage values, crystal detectors, and an rf power head were verified against each other and power balances compared.

The electron beam was noticeably intercepting the drift tube when output power exceeded approximately 100-MW. CONDOR simulations at peak output power predicted that 30 to 40-A would be collected on the drift tube shortly after the output cavity (1). Collector current data taken when the rf output is at 150-MW and when the rf is off, agree well with simulation. Interception is on the order of 40-A, or 5.7% of the total current (Fig. 5). According to calorimetric readings taken during operation at 3 μs at 150-MW rf, the intercepted beam power was approximately 2% of the collector power. With less than 100-MW rf applied, the transmitted beam power was approximately 99.6%. This means that the intercepted current at high rf power levels consists mainly of low energy electrons with an average energy of approximately 100-kV.

Output power was measured by calibration of a waveguide coupler and using detector crystals or a peak power analyzer. Instrumented water loads were used to absorb the rf and gave lower values of total power than did the waveguide couplers. To be conservative, the waveguide coupler calibrations were derated to the calibration of the water loads and essentially used for indicating pulse shape. On a 1-dB per division scale, the output pulse is quite flat, having less than 0.25-dB variation across the pulse top for 3-μs duration (Fig. 6).

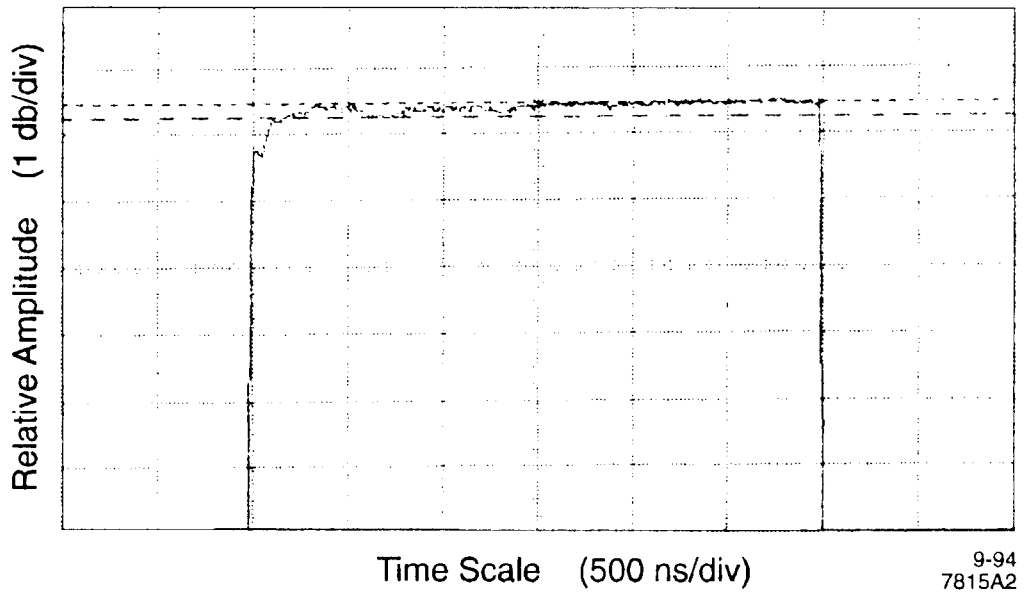

FIGURE 6. Detected rf output power from peak power analyzer at 150-MW operation.

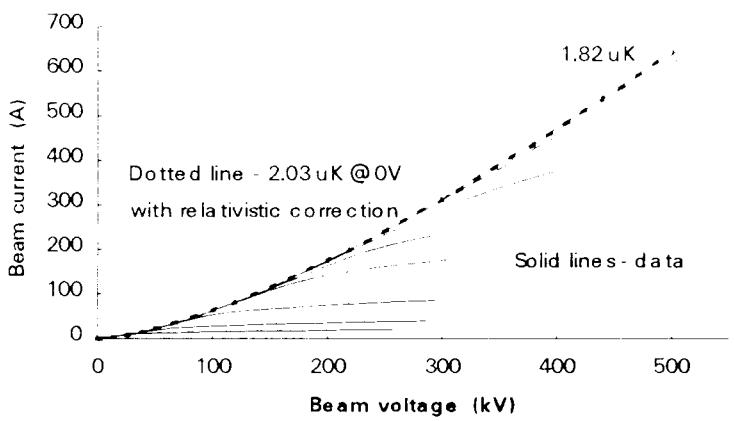

FIGURE 7. Klystron beam current and voltage data showing gun microperveance is ~1.82 at the design voltage of 535-kV.

The klystron gun performed similarly to the diode gun when temperature data is extrapolated and plotted with microperveance. At low beam voltages where relativistic effects are negligible, the microperveance is approximately 2.03, while at higher levels it falls toward 1.82 (Fig. 7). The slight difference in microperveance from the diode values can be attributed to mechanical tolerances and assembly procedures. The cathode heater required more power for a given cathode temperature due to the inclusion of the molybdenum shorting strips at the cathode edge.

FURTHER WORK

The second 150-MW klystron is currently under final construction at SLAC. There are three differences between the first and the second klystrons. To increase efficiency a two-cell output cavity structure will be used instead of a single gap. To increase life expectancy of the cathode if temperature-limited operation is desired, a scandate cathode will be used. Instead of copper drift tubes, two threaded and sandblasted stainless steel drift tubes will be inserted between cavities 3 and 4, and 4 and 5. The new drift tubes should increase the attenuation of rf modes traveling in the drift tube and thereby reduce the coupling between the three cavities. The added loss should either eliminate the oscillations shown in Fig. 3 altogether, or increase the threshold of oscillation and allow for more stable operation. Testing of the second klystron is scheduled to begin early in 1995.

ACKNOWLEDGMENTS

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REFERENCES

1. B. Aimonetti, S. Brandon, K. Dyer, J. Moura, D. Nielsen Jr., *CONDOR user's guide*, Lawrence Livermore Nat'l Lab., Livermore Computing Systems Document, April 1988.